DOE/MC/21181-1950, Vol. 8
(DE87001078)
Distribution Category UC-92a

Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities

Volume 8. Basin Analysis, Formation and Stability of Gas Hydrates in the Northern California Offshore

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Work Performed Under Contract No.: DE-AC21-84MC21181

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June 1986

PREFACE

This document is Volume VIII of a series of reports entitled "Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities." Volume VIII is a study titled "Basin Analysis, Formation and Stability of Gas Hydrates in the Northern California Offshore." This report presents a geological description of the offshore margin of Northern California, including regional and local structural settings, geomorphology, geological history, stratigraphy, and physical properties. It provides the necessary regional and geological background for more in-depth research of the area. Detailed discussion of bottom simulating acoustic reflectors, sediment acoustic properties, and distribution of hydrates within the sediments are also included in this report. The formation and stabilization of gas hydrates in sediments are considered in terms of phase relations, nucleation, and crystallization constraints, gas solubility, pore fluid chemistry, inorganic diagenesis, and sediment organic content. Together with a depositional analysis of the area, this report is a better understanding of the thermal evolution of the locality. It should lead to an assessment of the potential for both biogenic and thermogenic hydrocarbon generation.

Project Manager
Gas Hydrates

ACKNOWLEDGEMENTS

The authors are grateful to the U.S. Department of Energy, Morgantown Energy Technology Center, for the opportunity of participation in the gas hydrate research program. Particularly, we are thankful to Kathryn Dominic and Rodney Malone, for their comments and suggestions considerably improved the quality of the report.

Editorial input by Patrick Finley and drafting by Margaret Krason, both of Geoexplorers International, Inc., were also invaluable.

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EXECUTIVE SUMMARY

The following study entitled "Basin Analysis, Formation and Stability of Gas Hydrates in Northern California Offshore" is the ninth in a series of reports being prepared by Geoexplorers International, Inc. for the U.S. Department of Energy (DOE) - Morgantown Energy Technology Center (METC).

Northern California offshore was first identified as a potential gas hydrate-bearing location in 1983 by Kvenvolden and Barnard (1983) on the basis of personal communication with M. Field. Identification of the gas hydrates in this region has been made almost entirely through the analyses of seismic data where widespread bottom simulating reflectors (BSRs) were found. The BSRs, which are considered as a prime seismic feature indicating the presence of the base of the gas hydrate zone, have been identified in at least 3,000 km^2 of the outer continental margin of California, north of Cape Mendocino. Temperature and pressure conditions in the area of BSRs' occurrence conform with gas hydrate stability area within approximately 200 m of the subbottom sediments.

Although seismic coverage in the continental margin adjacent to Point Arena Basin (south of Cape Mendocino) is sparse, no evidence for the BSRs' presence has been found.

At the present time geological investigations in northern California offshore are based on the results of seismic surveys in onshore extensions of offshore basins and on some preliminary analyses of near-seafloor sediments. Only 7 wells have been drilled in the nearshore areas of Eel River Basin and Point Arena Basin (Table 1). These wells apparently were not located in the areas with gas hydrates.

Analysis of the existing and available geological data enables us, however, to draw several conclusions which have direct bearing on the gas hydrate potential in northern California offshore.

1. California offshore north of Cape Mendocino represents tectonically the area within an active subduction zone.

2. South of Cape Mendocino the major tectonic feature is right-slip lateral movement of the continental margin.

3. Two tectonically different positions of the continental margins greatly determined the structural features as well as geothermal regimes:

   a. Northern and central parts of the study area are underlain by metasedimentary rocks while the southern part has granitic basement. This feature is often related to the type of deformation within sedimentary sequences; faulting prevails on the south and folding is a more frequent deformation in the northern part of the study area.

b. Well defined geological elements of the continental margin (forearc Eel River Basin, occupying partly the shelf and upper continental slope, accretionary wedge, and lower continental slope) can be distinguished north of Cape Mendocino. In the margin south of Cape Mendocino the structural features are much less pronounced.

4. The lithostratigraphic profiles in the entire area show a prevailing shallow marine type of sediment.

5. Analyses of gas extracted from the near seafloor sediments in Eel River Basin seems to indicate the thermogenic origin of gas.

6. Lack of suitable geochemical data has not permitted unequivocal establishment of the hydrocarbon source rocks, their distribution, and hydrocarbon generation potential.

7. The migration of thermogenic hydrocarbons is mainly controlled by fault systems.

8. No significant hydrocarbon accumulations have been found in onshore extensions of the offshore Eel River and Point Arena basins.

9. Two distinctly different thermal regimes appear to control heat flow in continental margins north and south of Cape Mendocino. Significantly higher heat flow (1.5 - 2.0 HFU) occurs in the area adjacent to Point Arena Basin. This fact is explained by elevation of the top of the asthenosphere and lack of cooling effect due to subducted oceanic crust (Lachenbruch and Sass, 1980).

10. The geothermal gradient in the northernmost continental margin is calculated from gas hydrate stability conditions to be approximately 5.5°C/100 m.

11. Thermal regimes and hydrocarbon generation potential seem to constitute major conditions defining the potential for gas hydrates in northern California offshore.

12. Estimated gas potential reserves in the gas hydrate zone in northern California offshore amounts to 84.7 TCF.

TABLE 1.

SUMMARY OF BASIN ANALYSIS, FORMATION AND STABILITY OF GAS HYDRATES IN THE NORTHERN CALIFORNIA OFFSHORE

FACTORS / BASIN / SUB-BASIN	NORTHERN CALIFORNIA OFFSHORE	
	Eel River Basin and Adjacent Continental Margin	Point Arena Basin and Adjacent Continental Margin
BASIN ANALYSIS		
Location		
Longitude: latitude	124°20'W-125°00'W; 40°30'N-42°00'N	124°00'W-125°00'W; 39°00N-40°20'N
Areal extent, km^2	8,200 km^2	5,100 km^2
Geomorphology	Continental shelf and slope	Continental shelf and slope
Geomorphologic sub-unit		
Geology	Moderately defined	Moderately-poorly defined
Structural setting	Accretionary wedge, forearc basin	Forearc basin
Stratigraphy	Upper Jurassic-Quaternary	Upper Jurassic-Quaternary
Lithology	Mudstone, siltstone, sandstone	Shale, siltstone, sandstone
Sedimentary environments	*Shallow marine, occasionally deep marine*	Shallow marine
Sediment source	Coastal ranges	Coastal ranges
Rate of sedimentation, m/m.y.	0.5-1.0 cm/yr.	Undetermined
Sediment flux, $mg/cm^2/yr$	3,200 $mg/cm^2/yr$.	Undetermined
Organic matter flux, $mg/cm^2/yr$	Undetermined	Undetermined
Geochemistry	Undetermined	Undetermined
Total organic matter content, weight %	0.5-1.5	Undetermined
Source of organic matter	Marine	Undetermined
Preservation of organic matter	Undetermined	Undetermined
Depth of thermal maturity, m	Undetermined	Undetermined
Geochemical anomalies	Lack of data	
Sediment alteration	Undetermined	Undetermined
Physical and geophysical features	Undetermined	Undetermined
Sediment thickness, m	4,100	3,620
Porosity, %	Undetermined	Undetermined
Permeability, md (millidarcy)	Undetermined	Undetermined

TABLE 1.

SUMMARY OF BASIN ANALYSIS, FORMATION AND STABILITY OF GAS HYDRATES IN THE NORTHERN CALIFORNIA OFFSHORE

(continued)

FACTORS / BASIN / SUB-BASIN	NORTHERN CALIFORNIA OFFSHORE	
	Eel River Basin and Adjacent Continental Margin	Point Arena Basin and Adjacent Continental Margin
GAS HYDRATES FORMATION AND STABILITY		
Direct evidence	None	None
Type of gas hydrate occurrence	Unknown	Unknown
Indirect evidence	BSRs	Unknown
Bottom simulating reflector(s), BSR	Present	Not found
Areal extent of the bottom simulating reflector(s), km²	3,000	Not found
Quality of seismic data	Good to moderate	Poor to moderate
Inferred evidence	Temp., pressure, hydrocarb. gen. and lithology moderately favorable	Temp, pressure moderately favorable in limited areas
Location	124°45'W-125°20'W; 40°45'N-42°00'N	Undetermined
Sea water depth, m	600 - 2800	700 - 2700
Sub-sea bottom depth, m	200	Unknown
Hydrostatic pressure at sea floor, atmosphere (MPa)	72 - 336 (7.2 - 34.03)	84 - 324 (8.5 - 32.8)
Temperature at sea floor, °C	1.7 - 4° C	1.7 - 4° C
Gas hydrates host formation	Unknown	Unknown
Age of gas hydrates host formation	Pliocene-Quaternary	Undetermined
Gas hydrates stability zone	190 - 230 m	Undetermined
Initial porosity of gas hydrates host formation, vol. %	Unknown	Undetermined
Isotopic composition of gas, δ^{13}°C ‰	Undetermined	Undetermined
Pore water salinity, ‰ at depth m	3.3 - 3.5	3.4
Associated hydrocarbons	Undetermined	Undetermined
Time of gas hydrates stabilization	Undetermined	Undetermined
Source of gas hydrates	Undtermined	Undetermined
Evidence for free gas under gas hydrate zone	Undetermined	Undetermined
Estimated/inferred gas volume, at 25 °C/atm.	Undetermined	Undetermined
In gas hydrates	2.4×10^{12} m^3 (84.6 TCF)	Undetermined

INTRODUCTION

Offshore of Northern California is the region where gas hydrates have been inferred from the seismic data containing ubiquitous bottom simulating reflectors (BSRs). BSRs are considered by many authors to be features which depict the base of the hydrate zone. The study region covers at least 3,000 km^2 of the continental margin adjacent to the California coast north, of Cape Mendocino. The area with BSRs present occurs over such geological units as Eel River Basin, Klamath Plateau and the continental slope. The Pacific Ocean depth in the study region ranges from 800 to 2,900 m, the bottom ocean temperature, and geothermal gradient create thermodynamic conditions favorable for gas hydrate formation and stability. Such conditions occur in a subbottom zone approximately 190 - 230 m thick. On the other hand, the continental margin south of Cape Mendocino and adjacent to Point Arena Basin does not reveal the presence of BSRs.

Publicly available and geophysical geological data from the two areas are sparse and fragmentary. However, besides published data, we have extensively used information which is also publicly available but neither has been thoroughly studied and interpreted nor extensively used for the basin analysis and gas hydrate formation and stability. Specifically in this study we have used data included in the USGS Open Files, Atlas of Seismic Expressions of Structural Styles (Bally, 1983), as well as information from recent studies on gas hydrate potential in northern California offshore (Field and Kvenvolden, 1985; Kvenvolden and Field, 1981).

In this report, the geological factors which are critical for gas hydrate formation and stability are presented within a frame of basin analysis. The study revealed that a combination of various geothermal gradients, potential of the hydrocarbon generation and volume of potential hydrocarbon source rocks defined the favorable conditions for gas hydrate occurrence in the continental margin, north of Cape Mendocino and probably precluded their presence in California offshore adjacent to Point Arena Basin.

Gas potential reserves in the gas hydrate zone of northern California offshore have been estimated for 84.7 TCF and it may constitute a significant unconventional energy resource in the future.

PART I

BASIN ANALYSIS

Location

The northern California offshore is defined in this report by the extent of the two Neogene sedimentary basins, namely the Eel River Basin and the Point Arena Basin. The continental slope occurs west of the two basins and is adjacent to the shelf. The shelf, however, does not represent a prospective environment for gas hydrates and as such will not be elaborated in this study.

Eel River Basin (Figure 1) extends in a northern direction from near Cape Mendocino (lat. 40°30'N) for about 200 km to Cape Sebastian, Oregon (lat. 42°20'N). The average width of the basin is about 70 km.

Point Arena Basin (Figure 1) is adjacent to a major sedimentary basin to the south from Eel River Basin. The Point Arena Basin occupies the area from the Cape Punta Gorda on the north to the cape Point Arena. This basin is approximately 170 km long while its average width is 45 km (Figure 1). The outline of Point Arena Basin encompasses an area of about 7,650 km^2. Aerial extent of the Eel River Basin is approximately 10,360 km^2.

Geomorphology

The two sedimentary basins which will be presented in further course of this report are located within the Pacific Ocean continental margin of North America. Despite the common origin of both basins, their morphologies are different. The variations arise from the tectonic developments of the continental margin where both basins evolved. These differences necessitated the separate geomorphologic consideration which must be given to Eel River and Point Arena basins.

Eel River Basin

The bathymetric map of the continental margin part of Eel River Basin (Figure 2) shows major geomorphological features of the ocean floor in the region. Principal geomorphologic elements are: continental shelf, plateau slope, Klamath and Eel Plateaus and continental slope. Other highly visible geomorphologic components are two canyons (Eel Canyon and Mattole Canyon) located in southern part of the region (Figures 2 and 3).

The territorial limits of the Eel River Basin coincide approximately with the outline of the Klamath Plateau and the Eel Plateau. The two marginal

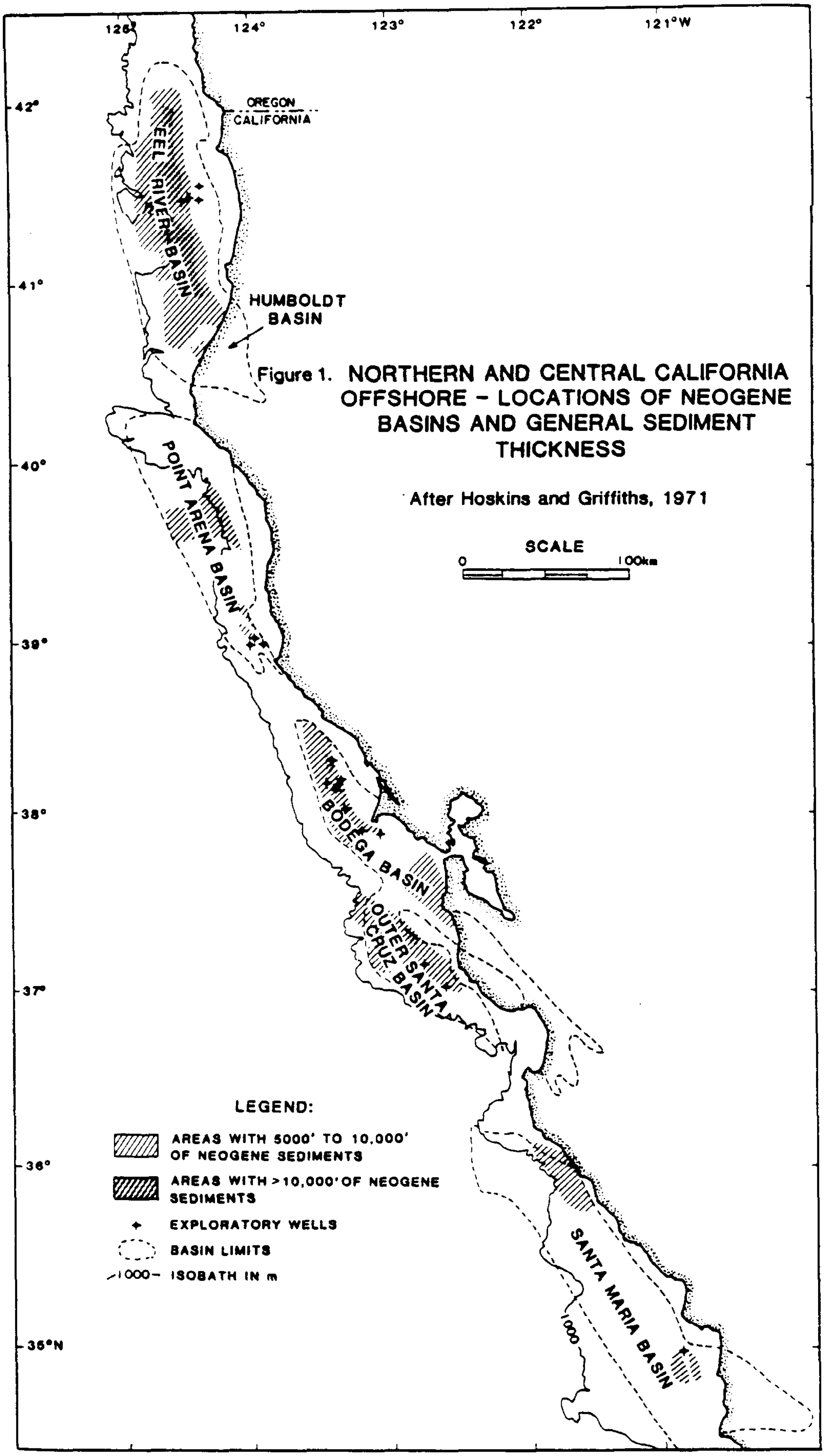


Figure 1. NORTHERN AND CENTRAL CALIFORNIA OFFSHORE – LOCATIONS OF NEOGENE BASINS AND GENERAL SEDIMENT THICKNESS

After Hoskins and Griffiths, 1971

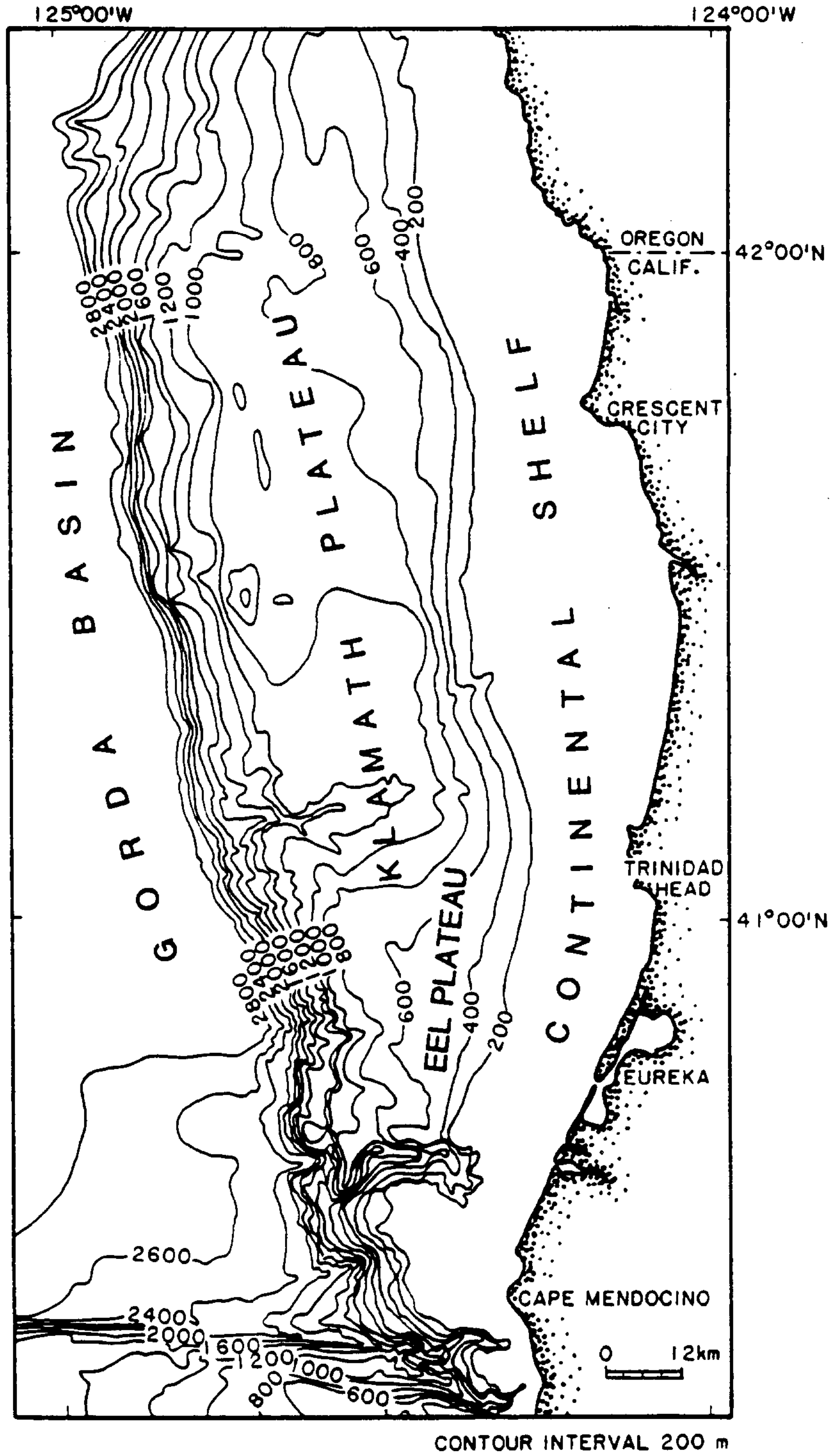


Figure 2. **BATHYMETRIC MAP OF THE CONTINENTAL MARGIN OFF NORTHERNMOST CALIFORNIA**

After Silver, 1971

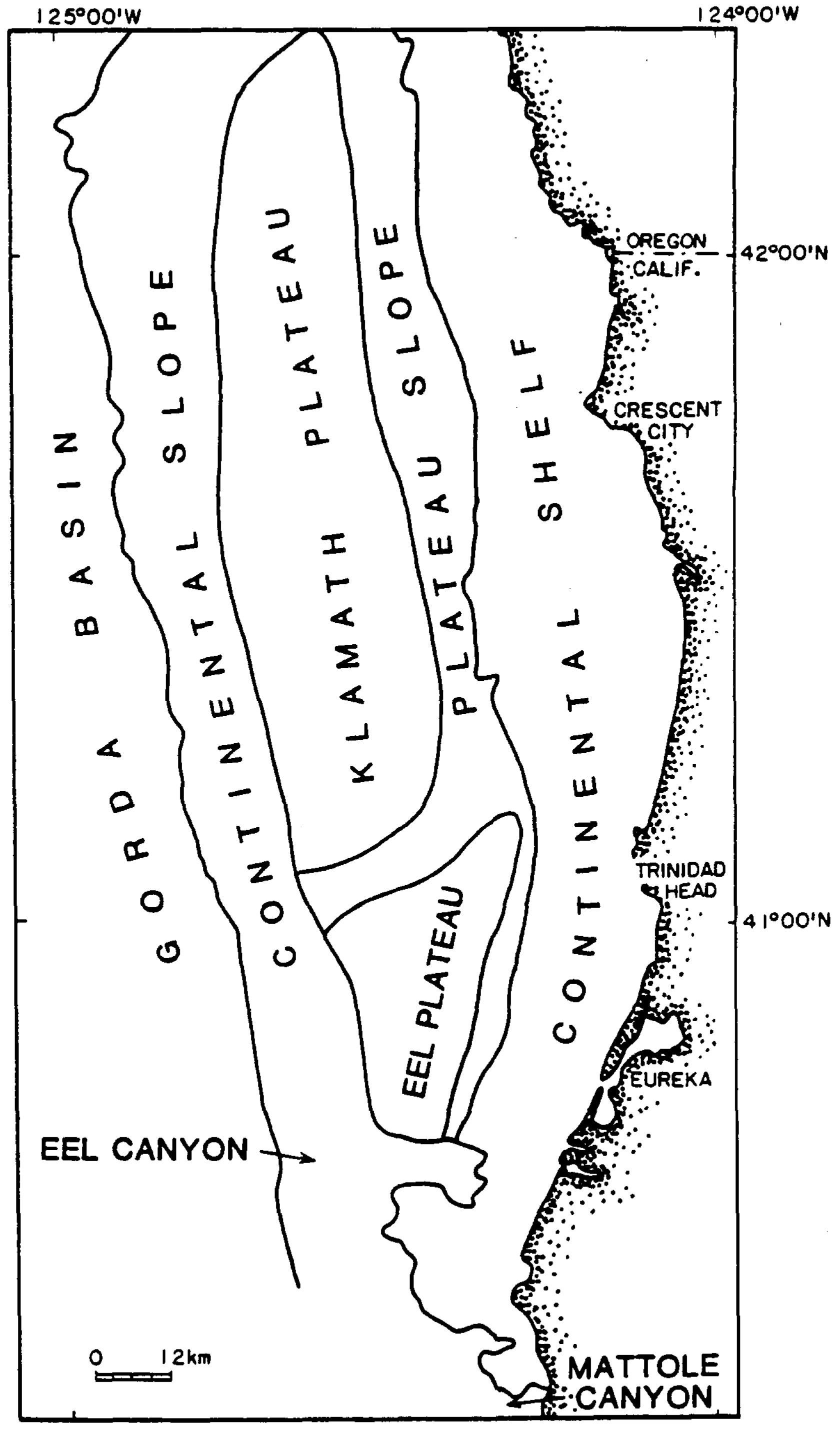


Figure 3. **PHYSIOGRAPHIC PROVINCES OF THE CONTINENTAL MARGIN OFF NORTHERNMOST CALIFORNIA**

After Silver, 1971

plateaus extend from Eel Canyon north to the latitude of Cape Sebastian in southern Oregon. The Eel Plateau which constitutes first of the two marginal plateaus in the region north of Eel Canyon is approximately 55 km long and 15 to 25 km wide. Ocean depths within the area vary from 500 to 800 m.

The Klamath Plateau is located north of the Eel Plateau. Both plateaus are separated by a gentle slope which leads into the area of the Klamath Plateau where ocean depths range from 700 to 1,100 m. The longer axis of the Klamath Plateau measures about 120 km while its width varies between 25 to 30 km. The Klamath Plateau slopes gently to the south displaying a relatively simple and uniform topographic pattern compared with the Eel Plateau. From east and west the plateaus are flanked by topographically transitional areas of plateau slope (east flank) and continental slope (west flank). The plateau slope inclines at 2 to 3° uniformly in most of its length with the exception of the area in the southern section of the Klamath Plateau where it steepens to 6°. West of the marginal plateaus a series of low ridges crops out on their seaward edge.

The steep continental slope separates the plateaus from the abyssal depth of the Gorda Basin. Eel Canyon is the largest submarine canyon cutting the northern California continental margin. The Mattole Canyon head extends to the coast and functions as a barrier to southward transported gravity flow sediment. Several smaller submarine canyons cut the edge of the plateaus and the continental slope. Among those canyons the Trinity Canyon present at 41°15'N latitude is the most pronounced.

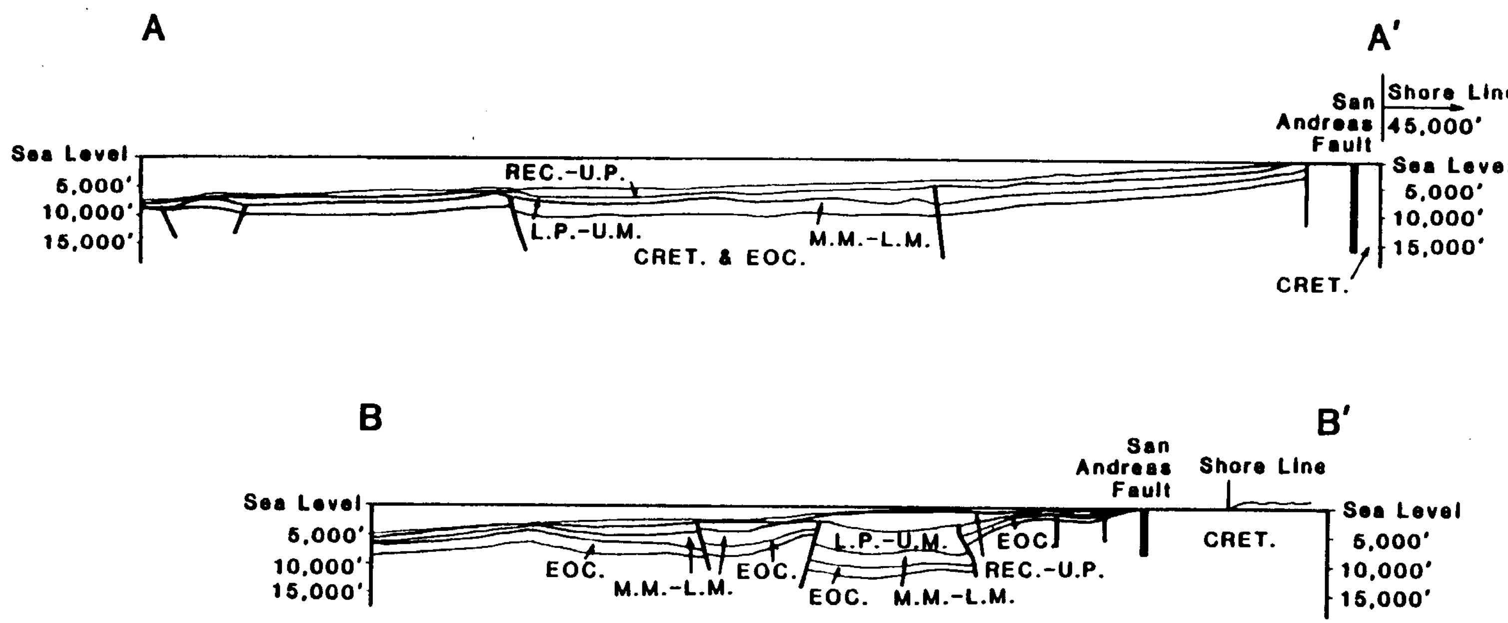
Point Arena Basin

This basin structurally belongs to the northern California continental margin and is bounded on east and north by the San Andreas Fault and the Mendocino fracture zone (Figure 4). The most characteristic feature of this margin is lack of continuous uplift on the oceanward flank. The Point Arena Basin does not constitute a depositional area in the same sense as all other Neogene age basins and along to central and northern California offshore. Geomorphologically the entire area of the Point Arena Basin continental margin displays sea-bed surface gently sloping toward abyssal plains (Figure 4).

Continental Slope

The continental slope west of Eel River and Point Arena basins displays different geomorphology which reflects two varying tectonic regimes under which the slopes were formed. Figures 5 and 6 show geomorphological profiles of the continental margin west of the Eel River Basin. The upper edge of the continental slope is very distinguishable. It features a number of ridges which can be traced along the margin to the Eel Canyon on the south (Figure 2). The continental slope is represented by the steep zone approximately 20 - 25 km wide, delimited by isobaths at 1,200 m and 2,800 m (Figure 5). Its geomorphological surface is still greatly determined by outcropping ridges or by buried ridges which are covered by turbidite sediment.

The continental slope west of Point Arena Basin has much less distinct character (Figure 4). In fact, the entire area is represented by a uniform surface gently dipping toward the abyssal plains with little geomorphological diversity.



LEGEND

REC. - RECENT
U.P. - UPPER PLIOCENE
L.P. - LOWER PLIOCENE
U.M. - UPPER MIOCENE
M.M. - MIDDLE MIOCENE
L.M. - LOWER MIOCENE
EOC. - EOCENE
CRET. - CRETACEOUS

LOCATIONS OF THE CROSS-SECTIONS ARE SHOWN IN FIGURE 6

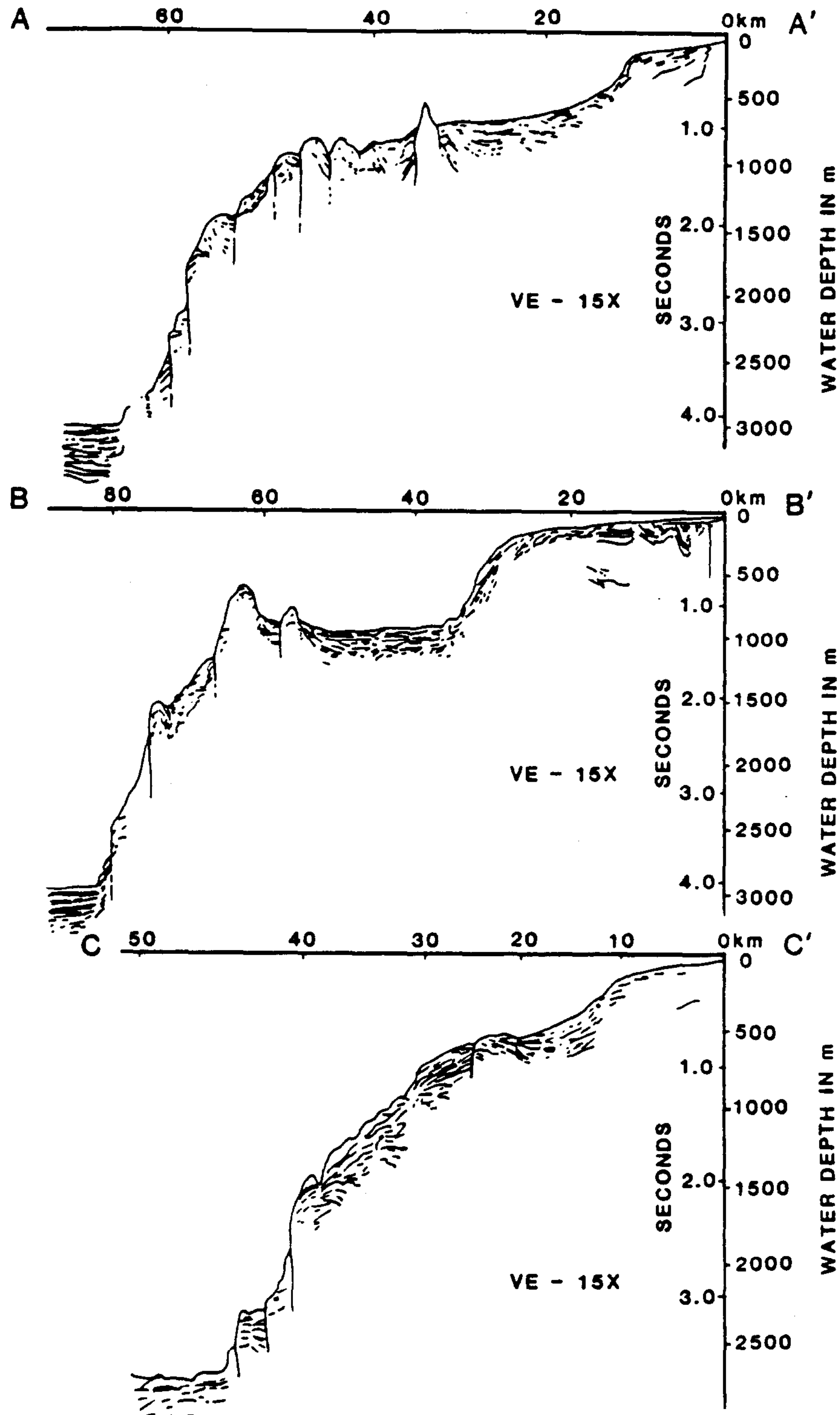
0 4 8 12km

HORIZONTAL SCALE

VERTICAL SCALE APPROX. THE SAME

Figure 4. **GEOLOGIC CROSS-SECTIONS IN THE POINT ARENA BASIN**

After Hoskins and Griffiths, 1971



FOR TRACK LINE LOCATIONS SEE FIGURE 6.

Figure 5. LINE DRAWINGS FROM SEISMIC PROFILES ACROSS THE EEL RIVER BASIN

After Silver, 1969

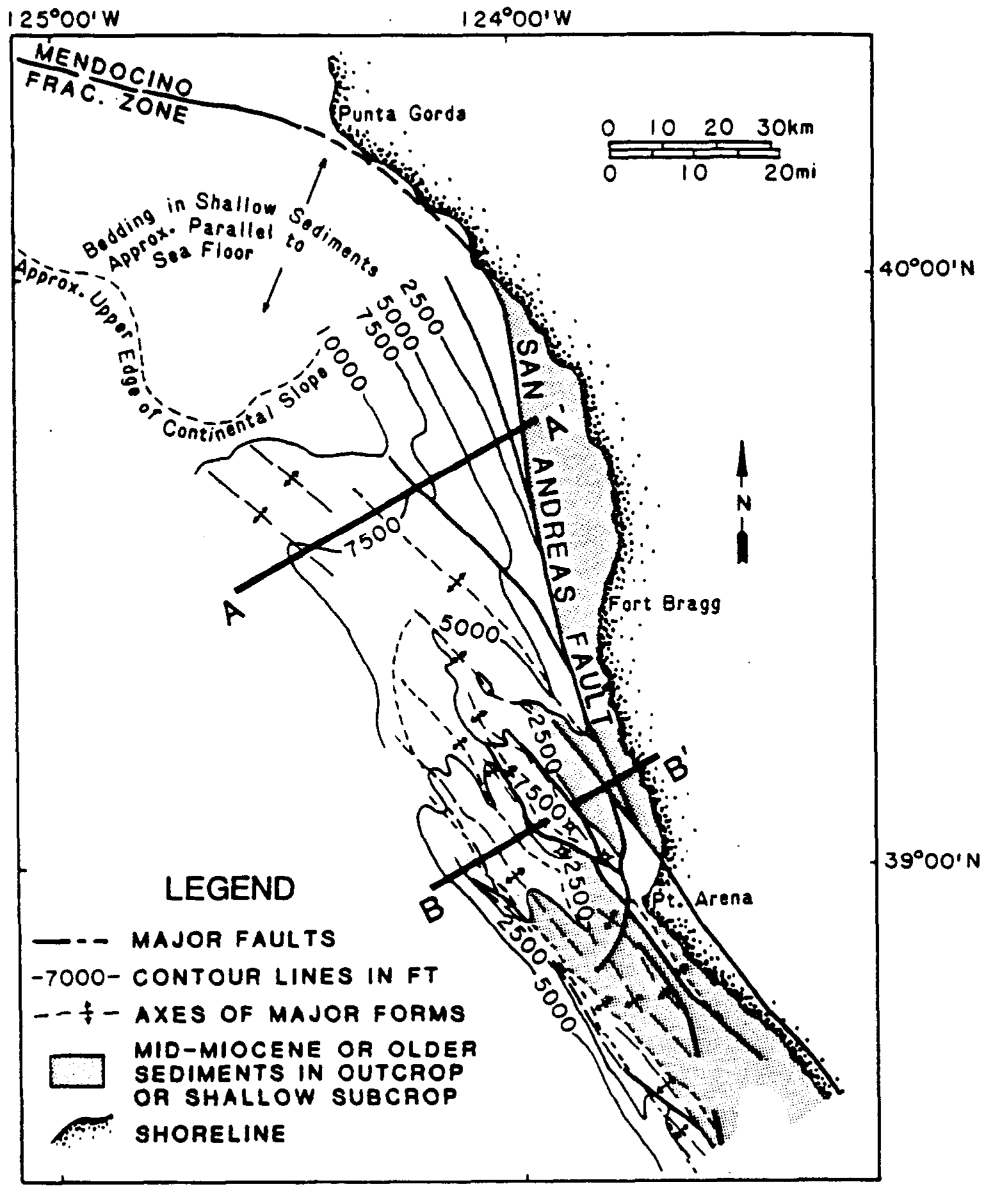


Figure 6. CONTOUR MAP OF BASE OF "UPPER MIOCENE" FORMATION IN POINT ARENA BASIN

After Hoskins and Griffiths, 1971

Structural Setting

The Eel River Basin and Point Arena Basin are two of the five major Neogene age basins of the northern and central continental margin of California. All these basins lie on the shelf or partially on the adjacent plateaus and continental slopes. Although all the basins have common origin, their various tectonic position requires the separate consideration which must be given to each of them. The latter is particularly important with regard to the Eel River Basin and the Point Arena Basin. The Eel River Basin represents a continental margin, the leading edge of which is in contact with the trench where active subduction takes place. The Point Arena Basin on the other hand represents a basin located in the region where the lateral translational movement is the prevalent dynamic feature of tectonism.

Before more detailed geological setting is presented, the regional plate-tectonic framework of the Eel River Basin and the Point Arena Basin is reviewed.

Plate-Tectonic Framework

The structural development of the continental margins of California is related to the motion of the Pacific and North American plates. One of the most interesting attempts for reconstruction of the plates' movement history was made by Atwater and Molnar (1973). These authors concluded that a well developed convergent margin with active subduction existed along the entire continental margin of California prior to 29 m.y. ago. At that time the spreading ridge system separating the Pacific and Farallon plates contacted the North American plate (Figure 7). As the spreading system moved eastward relative to North America two triple junctions were formed. Further movement of the Pacific plate to the east caused the migration of the two triple junctions in opposite directions. When the triple junctions moved away from each other and the Pacific plate was finally welded to the North American plate further relative movement of the two plates was compensated for by right lateral shear along the strike-slip faulting system. In this process an increasing length of the margin was subjected to right lateral translational shear (Figure 6). The San Andreas fault became a major faulting system along which the right lateral shear between the Pacific and North American plates continues until now. Silver et al. (unpub. data, after Blake et al., 1978), in the attempt of reconstructing the translational movement of the Pacific plate, have documented changes in azimuth of shear between the Pacific and American plates during the last 10 m.y. This azimuth according to Silver et al. (1971) changed from a more northerly to northwestern direction. The consequence of such alteration of the shear directions was that the Pacific plate motion relative to the San Andreas fault between 21 and 10 m.y. ago had a slightly compressional effect on California while during the time interval between 10 m.y. to the present it had an extensional effect in the entire region, with the exclusion of Baja California where subduction of the Farallon plate was in progress.

Despite significant uncertainties, the plates' movement reconstruction provides alternative mechanisms responsible for formation of a series of Neogene structural basins including Eel River Basin and Point Arena Basin

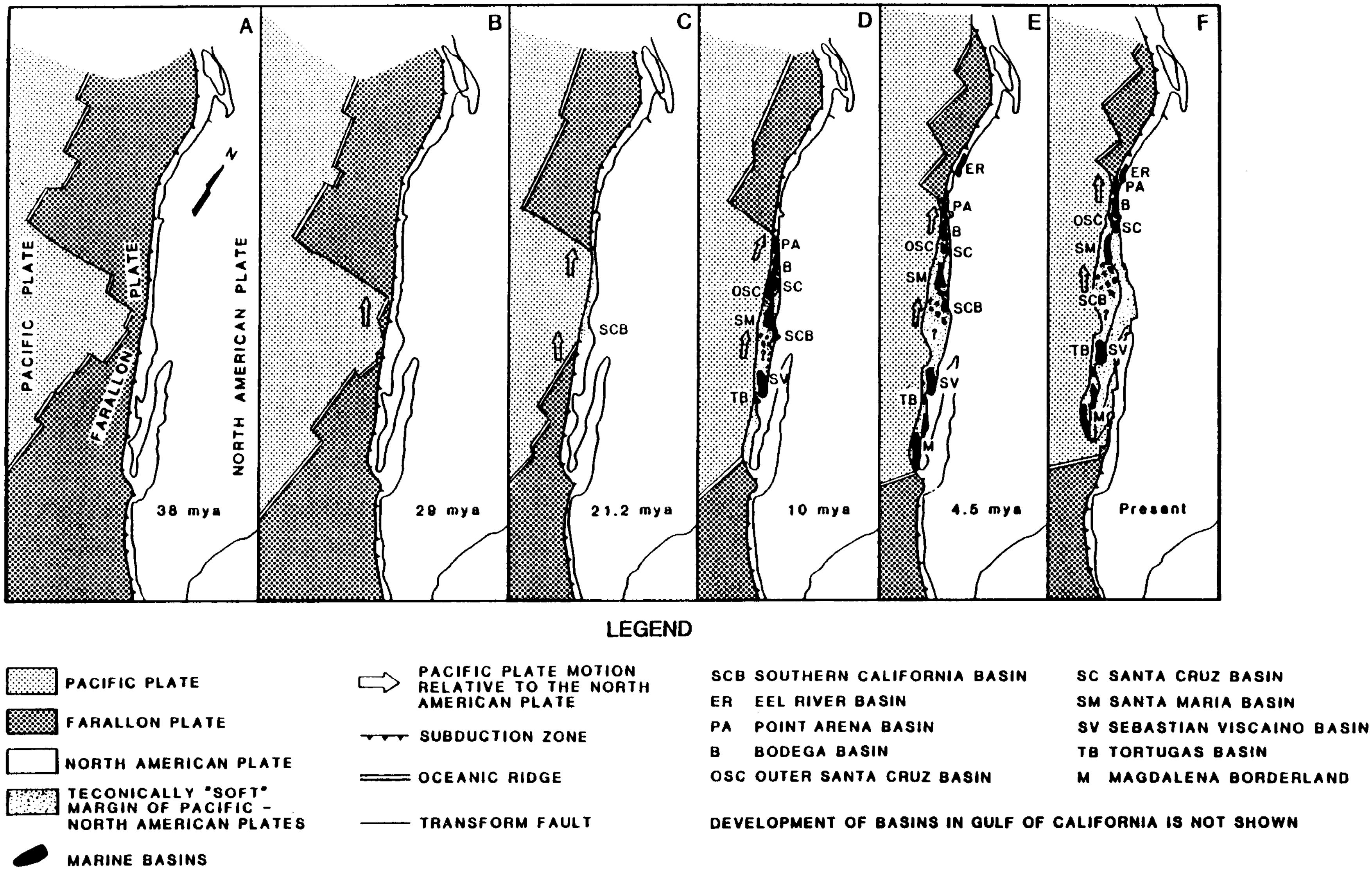


Figure 7. DEVELOPMENT AND LOCATION OF NEOGENE BASINS FORMED IN TECTONICALLY "SOFT" ZONE

After Blake et al., 1978

along the continental margin of California. There are three conceivable types of mechanisms which could have led to the formation of the marginal basins:

- contact of the spreading-rise crest with the continental margin

- changing plate motions

- combination of the two above mechanisms.

The first alternative should result in the formation of a series of progressively younger basins in a north to south direction as the two triple junctions migrated apart from each other. The second alternative should have produced a system of synchronous basins about 13 to 8 m.y. ago. Despite much evidence gathered indicating that the second alternative took place in the northern and central California offshore, numerous investigations suggest that both mechanisms were important in evolution of the continental margin.

Structural Development of the Continental Margin of California

The inception of the marginal Neogene basins along California's offshore and their evolution is related to the development of the continental margin. Therefore it seems that recapitulation of the major geological events which occurred prior to the Tertiary time and led to the formation of the basement for the younger basins within the continental margin is appropriate.

A relatively simple and coherent model of the development of the continental margin of California has been presented by Orwig (1976). According to this author the major uplift of the North American Cordilleran fold belt took place during the final stages of Late Jurassic diastrophism. This event completed the geosyncline-orogenic cycle initiated in early Paleozoic times and was followed by a cycle of active erosion, sedimentation, and deformation processes on the eroded western flank of the older terrane. Initially the Pacific margin basin was formed as a narrow shelf which separated the cordillera from the deep open Pacific Ocean. The incipient shelf depressions were filled with the sediment derived from the highlands. The excessive sediment which could not be deposited on the shelf was transported beyond the shelf edge and settled in the form of deep-sea fans. During the Early Cretaceous the shelf was widened as a result of the erosion of the cordilleran mountain front. The next important tectonic event in the region was marked by westward thrusting of a large crustal block of the Klamath salient which broke the cordillera along north-trending faults. This event occurred near the end of Valanginian time. As a direct consequence the Valanginian shoreline was offset seaward (Jones and Irvin, 1971). The Hauterivian sea transgression which succeeded the submergence of the Klamath salient realigned the early Cretaceous northerly trend of the shorelines. During the Hauterivian and Albian stages the widening shelf permitted the development of distinct local depositional troughs separated by the shallowly submerged Klamath salient in the area of Oregon and California. The subsidence of these depocenters was more than compensated by the continuous uplift of the cordillera. At the same time the abundance of the detrital material carried from the mountains caused the filling of the shelf depressions to a thickness of 5 - 10 km and the building of previously formed deep-sea fans off the continental slope into a thick and broad continental apron. Continued subsidence of the depositional areas of the continental margin and transgression of Late Cretaceous seas were accompanied by intervening uplift, thus contributing to the further differentiation of previously formed basins. The clear distinction of individual basins in the central and southern areas of California has been obliterated by uplift, erosion, or later metamorphism. The emergence of the sediments deposited in the continental margin during the Cretaceous, which occurred in early Paleogene time, was vigorous. During this event intense folding, high-angle reverse faulting, and local thrusting took place. Also, diapiric structures were formed. All these deformed continental margin formations, commonly referred to as the Franciscan complex (Berkland et al., 1972), constitute the basement of the Eel River Basin and underlie the continental slope west of the basin. At least partially different basement underlies the continental margin which contains the Point Arena Basin. The continental margin of northern California south of Point Conception is underlain by granitic basement, which is known from the onshore areas as the Salinian block (Page, 1970). The Salinian block is considered by many authors as a part of Sierran arch basement dislocated by major right lateral strike-slip movement along the San Andreas faulting system (Hill and Diblee, 1953; Page, 1970).

The difference in the type of basement which underlies the continental margin of northern California offshore together with the fact that north of the Mendocino fracture zone, the continental margin is limited by an active subduction zone while south of the Mendocino fracture zone lateral slip movement prevails (Silver, 1969) probably has an important bearing on hydrocarbon generation and subsequently on gas hydrate potential.

Only remnants of a once thick marine Cretaceous sedimentary section are present along the length of the northern continental margin of California. These rocks are usually dense and show signs of previous deep burial (Hoskins and Griffith, 1971). Their major erosional stage occurred in pre-Eocene time. Marine clastic sediments were extensively deposited on the shelf during Eocene time. In early Oligocene most Eocene sediments were removed as a result of a period of uplift and erosion of the shelf. Extensive sea transgression to the east across the eroded shelf brought early Miocene marine sedimentation. In the late middle Miocene the initial uplift of the continental margin of California occurred which led to differentiation of the shelf surface and gave birth to six basins in the late middle Miocene, including the Eel River Basin and the Point Arena Basin. Each of these basins extends onto the contemporary onshore areas where their eastern limits can be delineated. The nature of middle Miocene sediments also strongly suggests the presence of such a boundary on the western flanks of the basins. Generally the shelf was subsiding from early Miocene until late Pliocene. Only in some eastern areas of the shelf was the subsidence interrupted by minor sea regressions at the end of early Miocene and during early late Miocene time. The continuous subsidence and deep marine sedimentation lasted in the western half of the area to the latest Pliocene and were followed by uplift and structural deformation. Further deformation of the sedimentary sequences of the California continental margin have taken place throughout the Quaternary.

The major force causing deformation in the continental margin north of Mendocino fracture zone is most likely underthrusting of the margin by the Gorda Plate and locally by shearing and shale diapirism (Field et al., 1980). In the continental margin area south of the Mendocino fracture zone where the sediment deformations are much less pronounced the mechanism of their formation is probably driven by the lateral slip strike movement.

Continental Margin North of Mendocino Fracture Zone. Figures 5 and 8 show the major structural features of the continental margin north of the Mendocino fracture zone. One of the characteristic features is the presence of a ridge or a series of ridges at the oceanward edge of the marginal plateaus. The structural features of these ridges which conform with their topography seem to suggest that at least some of them are genetically associated with folds.

The folds are mostly discontinuous and cut by deep faults with the west side downthrown. These folds and faults are dominating features of deformed continental slope.

Fold axes in the Eel River Basin follow a general trend in north-northwest trend which is parallel to the main axis of the basin. These structures display a variety of folds ranging from broad and gentle to narrow and tight, mostly symmetrical. Many folds can be mapped for distances of 10 to 15 km and can be traced on seismic sections for more than 25 km. Field et al. (1980) distinguished three types of folds in the Eel River Basin:

a. Folds represented by the anticlines expressed as sea-floor bulges, knolls and ridges on the plateau which are on the order of 10s to 100s of meters high. These forms are presently undergoing uplift and/or piercement by deeper lying shale beds. The sea-floor bulges, knolls and ridges are characteristic for the area of outer and south-central plateaus of the Eel River Basin.

b. Folds which extend to the sea floor and had been truncated by erosion after folding episodes. These structures are mostly of Tertiary and pre-Tertiary age. They are characteristic of the areas of the Eel River Basin where water depth does not exceed 200 meters.

c. Folds buried beneath undeformed sediments. This type of structural configuration features the shelf areas and central plateaus of the Eel River Basin.

The study of ocean-floor relief in the continental margin north of the Mendocino fracture zone enabled Field et al. (1980) to formulate some conclusions pertaining to tectonic deformation of sediments in the Eel River Basin:

1. A significant amount of ocean-floor relief (up to 200 m) is directly related to the folding system.

2. A folding system including deformation of Holocene sediments makes it evident that the Eel River Basin has been affected by compressional forces throughout at least the Quaternary, and perhaps longer.

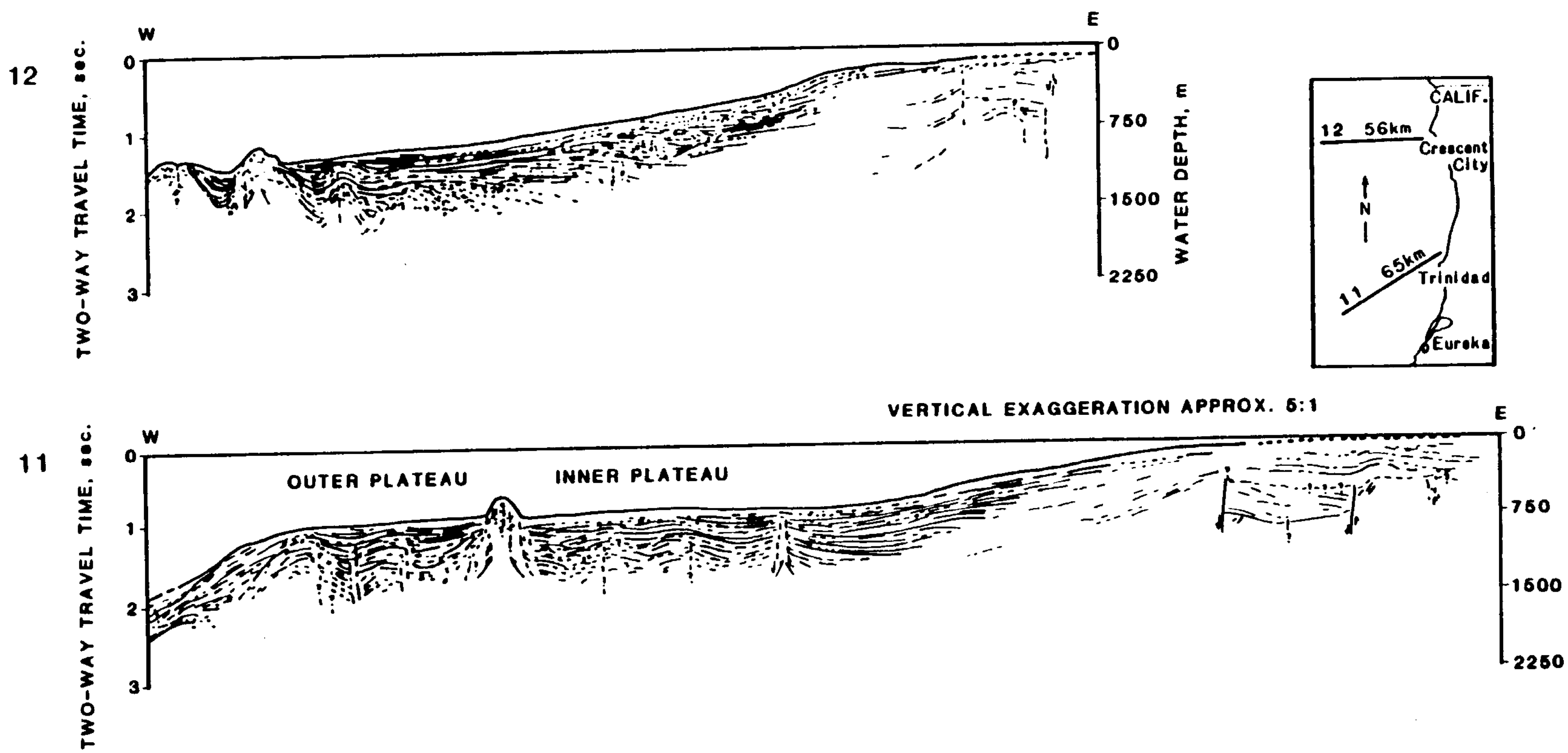


Figure 8. **LINE DRAWINGS OF ACOUSTIC PROFILES ACROSS EEL RIVER BASIN**

After McCulloch et al., 1982

3. The deformation processes continue at the present time, and it is primarily caused by underthrusting of the continental margin by the Gorda Plate. Locally this deformation may also be activated by shearing or shale diapirism.

Faults. Numerous faults cut geological formations of the Eel River Basin and adjacent terranes (Figure 9). Many of these faults produced offsets in the ocean floor, indicating recent time of their inception. The limited core and seismic data available from the Eel River Basin are not sufficient to establish ages of seismic units and subsequently the precise faulting ages. The age of various faults shown in Figure 9 was interpreted from the age of the sediment unit, its deformation, unconformities, and on the basis of age data of the benthic foraminifers. The map shown in Figure 9 indicates that the central parts of the Eel and Klamath Plateaus have fewer faults than do either the outer plateaus or continental shelf. Most faults on the shelf do not display much evidence of vertical displacement after the Holocene erosional event. These faults exhibit a lack of a deep vertical separation. The explanation of this fact could probably be the presence of a right lateral motion component associated with earthquakes beneath the shelf, shown by Bolt et al. (1968). Faults on the central part of plateaus are generally widely spaced and do not show the offsets in the sea floor. Their ages range from Pliocene to Holocene (Field et al., 1980).

In the entire area of the continental margin north of the Mendocino triple junction, faults are most common on the outer plateaus and upper slope. Most of these faults have been interpreted as being associated with shale diapirism (Field et al, 1980). West-side-down faults can be traced for long distances on the outer slopes of the continental margin. Biddle and Seely (1983) interpreted a number of thrust faults between the base of the slope and upper continental slope (Figure 8 and 9) north of the latitude 41°. Such interpretation was based on the model of generalized subduction complex proposed by Seely et al. (1974) and further developed by Seely (1977). According to this model relatively intensive continental accretion occurs when the rates of underthrusting and trench sedimentation are high. Subsequently the trench inner slope builds quickly seaward by "sweeping up" trench sediments through the thrust mechanism. Accreted sediments which constitute an additional load on the underthrusting oceanic plate cause that plate to downbend. This subsidence would cease once the subduction rate is slow and isostatic rebound occurs at this point. Previously formed detached faults would facilitate the uplift of the accreted sediments during periods of active underthrusting.

Shale Diapirism. Shale flowage and diapirism have been identified in the continental margin of Oregon and Washington states (Rau and Grocock, 1974). Hoskins and Griffiths (1971) suggested the possibility of the shale diapir occurrences also on the continental margins of northern California. Yet another group of authors (Field et al., 1980) pointed out that many ridges and knolls on the Eel and Klamath plateaus are diapiric in nature. Also it was found that younger sediments overlying the diapiric forms were uplifted and subsequently exhibit noticeable ocean-floor relief (Figure 9). As the evidence for the presence of shale diapirism in the area, the following features of the presumed forms have been cited by Field et al. (1980):

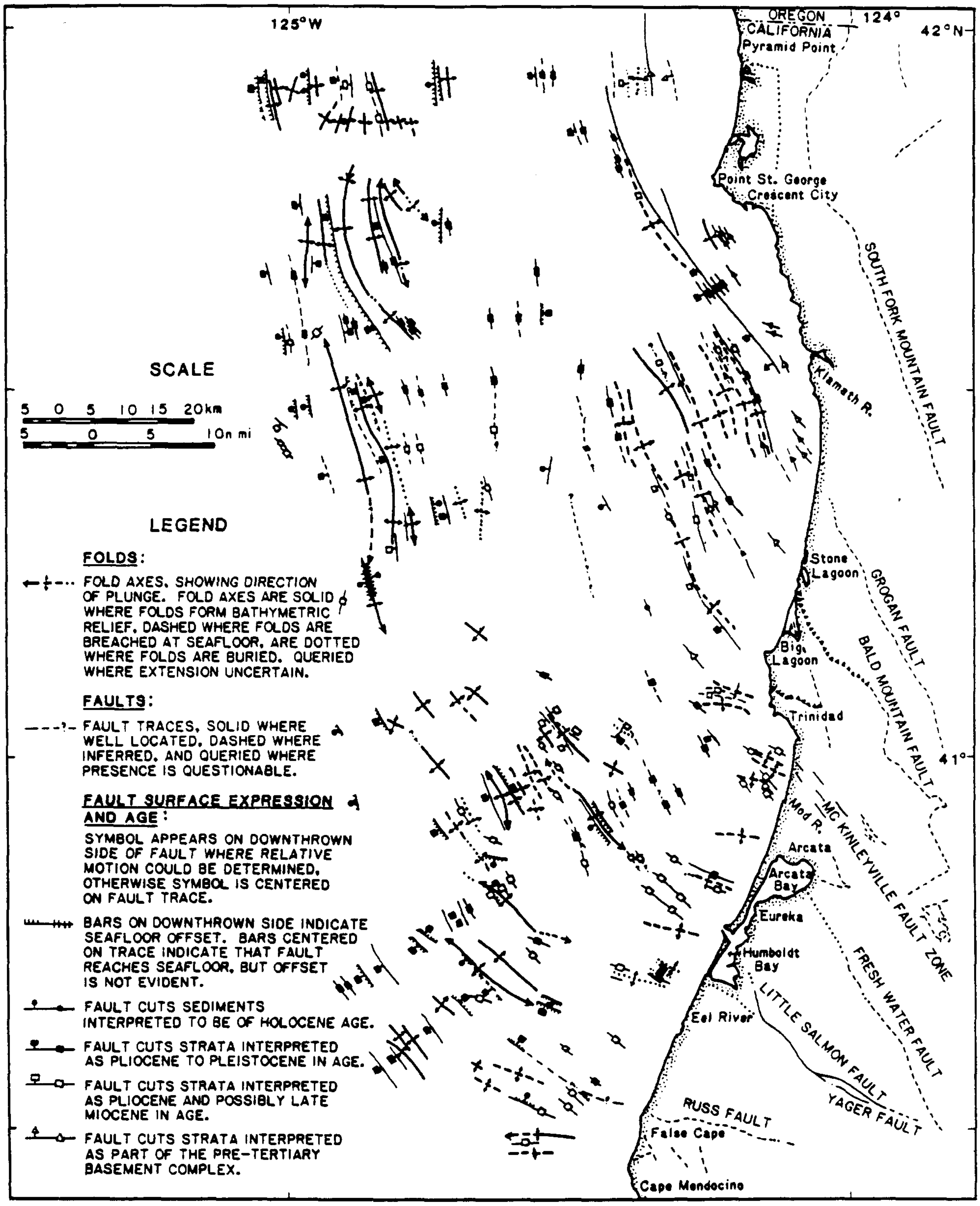


Figure 9. **PRELIMINARY STRUCTURAL MAP OF THE NORTHERN CALIFORNIA CONTINENTAL MARGIN**

Modified after Field, 1980

1. Lack of internal structure. No evidence of bedding in contrast with the rest of the basin.

2. Frequent lack of sediment cover. Despite high rate of sedimentation in offshore of northern California, many ridges have no sediment cover. This probably means that the processes of shale diapirism are active at the present time.

3. Irregular surface of the diapiric ridges. Extreme irregularity of the surface seems to indicate recent flowage.

4. Age and lithology. Sediments recovered from exposed ridge tops are represented by cohesive muds of Pliocene age.

5. Sediment deformation. Flat lying sediments on the plateaus show signs of being turned upwards at the base of diapiric ridges.

Slumps and Slides. These features have strong impact on structural setting of near sea-floor sediments of the continental margin offshore of northern California (Figure 10). Many authors have discussed the omnipresence of slumps and slides in modern shelves, slopes, and continental rises around the world (e.g. Lewis, 1971; Haner and Gorsline, 1978; Carlson and Molnia, 1978). Slides in contrast to slumps do not have internal structural deformation after the sediments are moved from their original location. The presence of slumps has been observed on slopes as gentle as 1° (Heezen and Drake, 1964). In northern California offshore the zones of slumping reach sizes from 1,000 m to tens of kilometers on a side. Their presence has been noted at water depths from 200 to 750 m on the shelf edge, plateau slope and Eel and Klamath Plateaus. Field et al. (1980) distinguished three major zones of slumping in the Eel River Basin:

1. Area west of Crescent City
2. Area west of Mad River
3. Area west of Eureka

These three major slump zones are composed of rotated and translated sedimentary units which are located below the shelf edge and extend out onto the marginal plateau (Figure 10). The northernmost slumping zone located west of Crescent City covers approximately an area of 250 km^2. It is 20 to 30 m thick and overlies well bedded structurally undisturbed sediment. The lack of undisturbed sediment overlying the slumps indicates the young age of the latter forms. The slumping area identified west of the Mad River probably covers an area of over 70 km^2. A third major slumping zone covers over 185 km^2 west of Eureka and extends from the surface down to at least 65 m and possibly to 200 m below the sea floor. Smaller slumps 300 to 375 m wide are also present along the continental slope. The continuity of these slumps is not fully known. Buried slumps were identified by Field et al. (1980) on seismic reflection records from the above described areas of surface slumps. Subbottom depth and thickness of buried slumps vary greatly, but usually they are 50 m thick and extend as deep as 370 m below the ocean floor (Field et al., 1980).

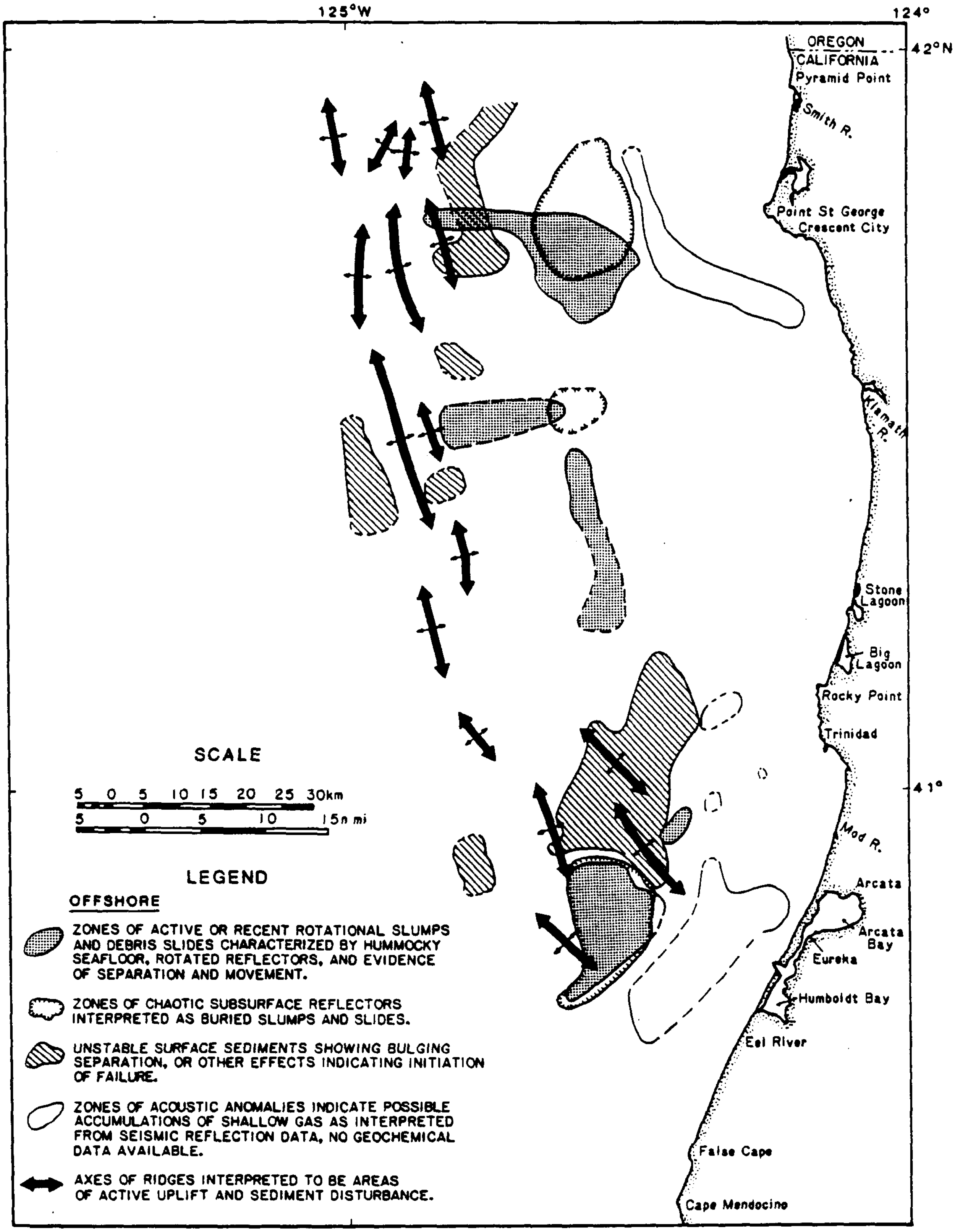


Figure 10. **AREAS OF SEAFLOOR AND COASTAL INSTABILITY ON THE NORTHERN CALIFORNIA CONTINENTAL MARGIN**

After Field et al., 1980

Structural Features of the Continental Margin South of the Mendocino Fracture Zone. The continental margin south of the Mendocino fracture zone represents the region where right lateral movement along San Andreas fault system constitutes a major factor of the structural development. This fact seems to have played a major role in structural development and subsequently in conjunction with other factors it has had a significant bearing on hydrocarbon potential of the region. Despite the fact that the continental margin between 39°N (Point Arena) and the Mendocino fracture zone (MFZ) is geologically far less known than the one north of the MFZ, several structural differences have been detected based on existing data. Point Arena Basin occupies a major part of the continental margin south of MFZ. The western flank of the Point Arena Basin cannot be precisely delineated other than by assuming certain isobaths as the continental slope dips gradually toward the abyssal plain (Figure 6). The pre-Cretaceous metasedimentary rocks constitute the basement in the northern part of Point Arena Basin. The southern part of the basin is underlain by granitic rocks (Hoskins and Griffith, 1971). The boundary between the two parts of the basin has not been unequivocally established. The Cretaceous and Eocene marine sediment sequences thin markedly toward the north of the basin, probably due to pre-Eocene erosion. Pre-Miocene erosion left only remnants of a once thick deeply buried marine shale and sandstone section. The Oligocene was a period of uplift and subsequent erosion in the area of Point Arena Basin. The early Miocene marine transgression is marked by basal sand which was later overlain by the marine sandstone of reservoir quality. The marine sedimentation continued through at least the early Pliocene time and was followed by a period of uplift and erosion in late Pliocene. During this time the structural features of the basin were developed. In general the compressional features in the structural setting of the Point Arena Basin are much less distinguishable than in the area north of the Mendocino fracture zone. Seismic reflection profiles across the Point Arena Basin (Silver, 1971; Kulin and von Huene, 1971) suggest that Miocene and younger strata are relatively little deformed. Horizontal forces were the most probable cause of the long folds and associated large fault formation which parallel the San Andreas fault system west of the Point Arena cape. The Neogene structure seems to be relatively more complex at the south end of the basin while it becomes simple to the north. According to Field et al. (1980) tectonic deformation of the southern end of the basin may have started with the uplift which produced the early late Miocene unconformity. The major high angle reverse faults and folds parallel to the main basin's axis were formed in upper Pliocene time. In the northern part of the Point Arena Basin where the two fracture zones (i.e. Mendocino fracture zone and San Andreas fault zone) converge, the limited seismic data suggest that the strata probably form an uncomplicated south-west dipping homocline.

Lithostratigraphy

Little has been published on the ages and lithological sequences of the continental margin of northern California. The lithostratigraphic development of these areas was reconstructed largely from exposures in the onshore extensions of the offshore basins. Direct information pertaining to the lithostratigraphy of the continental margin of northern California has been obtained from seven exploratory wells drilled in Eel River and Point Arena basins (Table 2). The fullest accounts yet on the lithostratigraphy of northern California offshore has been published by Hoskins and Griffith (1971) and Silver (1969, 1971a, 1971b). In 1977 McCulloch presented the stratigraphic synthesis of the areas based on the above references.

TABLE 2.

EXPLORATORY WELLS DRILLED ON OCS LAND
(After 1963 Federal OCS Lease Sale 53)

Company & Well Name	Basin	Total Depth		Spudded	Abandoned
		Meters	Feet		
Humble P-012-1	Eel River	903	2964	7-30-64	8-19-64
Humble P-007-1	Eel River	273	897	7-01-64	7-27-64
Shell P-019-1ET	Eel River	1981	6500	7-11-65	7-30-65
Shell P-014-1ET	Eel River	2249	7377	6-17-65	7-07-65
Shell P-032-1ET	Point Arena	2106	6909	11-26-66	1-13-67
Shell P-033-1ET	Point Arena	1438	4719	10-24-66	11-11-66
Shell P-030-1ET	Point Arena	3242	10,636	3-10-65	6-10-65

Eel River Basin Lithostratigraphy

A generalized stratigraphic profile from Eel River Basin is shown on Figure 11. Basement rocks in the onshore part of Eel River Basin consist mostly of massive graywacke with some chert, basalt greenstone, shale, limestone and schist, which can be found in the coastal and central belts of the Franciscan complex. These rocks are of Late Jurassic to Eocene age (Berkland et al., 1972). There are indications that similar lithostratigraphic rock sequences underlie the basin offshore (McCulloch et al., 1980).

The Yager Formation of Eocene age was found to be in fault contact with Franciscan basement rocks of the central belt in the lower Eel River area (Evitt and Pierce, 1975), however in a short distance to the southwest the formation depositionally overlies the Upper Cretaceous-Eocene rocks of the coastal belts (Irwin, 1960). The lithological sequence of the Yager Formation consists of dense, well-indurated mudstone, siltstone and shale and

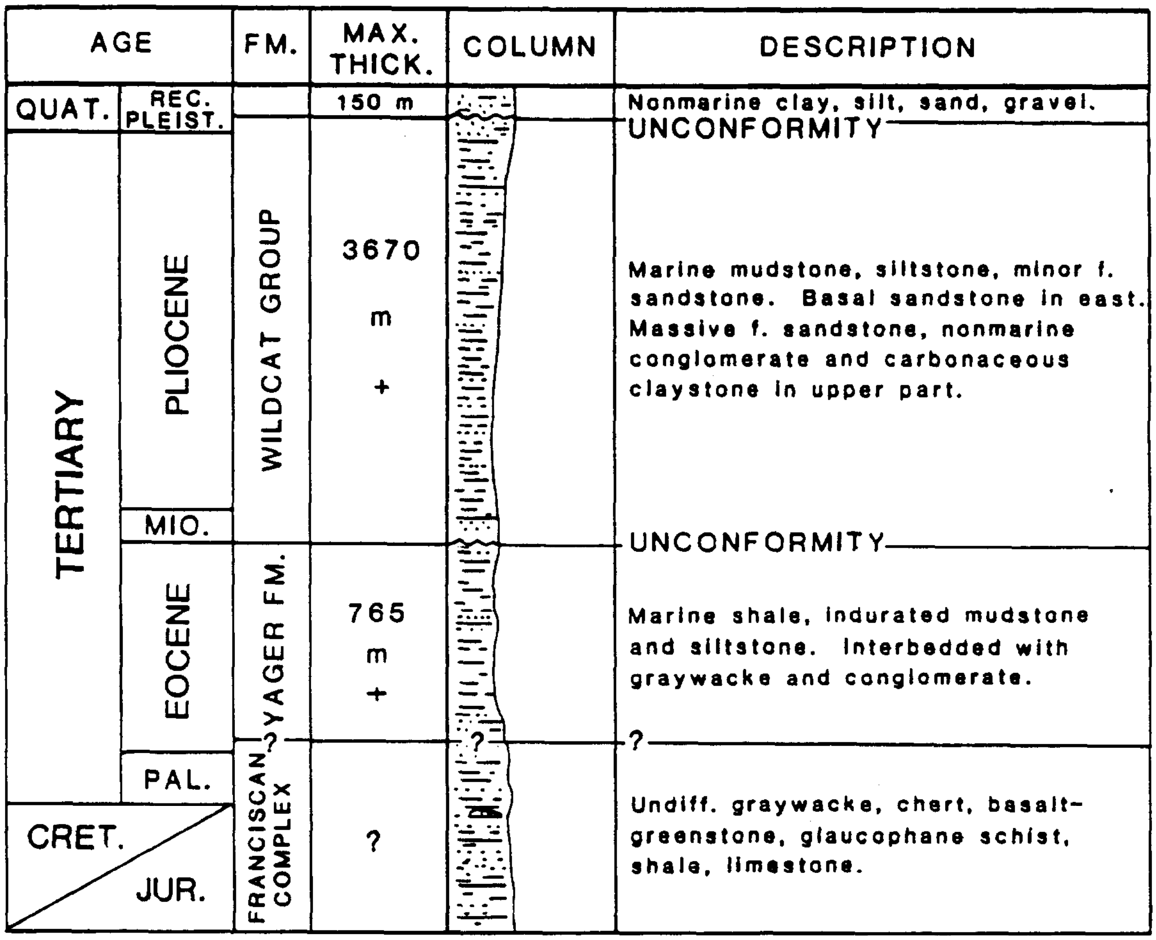


Figure 11. **GENERALIZED LITHOSTRATIGRAPHIC PROFILE OF THE EEL RIVER BASIN**

After Hoskins and Griffiths, 1971

contains some graywacke and conglomerate with local Franciscan detritus. Thickness of the formation is at least 765 m and perhaps locally as much as 3,060 m.

The Wildcat Group conformably overlying the Yager Formation is represented by a sequence of mostly marine late Miocene to Pleistocene sediments. The whole sequence is about 3,760 m thick. Prevailing lithologies are weakly consolidated mudstone, siltstone and claystone with subordinate amounts of sandstone and conglomerate, and minor amounts of lignite and tuff. The lithological sequences of the Wildcat Group show the record of a northward marine transgression during late Miocene followed by alternate deepening and shallowing of the basin, sea regression during late Pliocene and finally the emergence of the area when the marginal marine and nonmarine deposition in late Pliocene and Pleistocene time took place. Final deposition of the Wildcat Group sedimentary sequence was marked by the basin margin warping and uplift which continued into the Pleistocene time, culminating in major basinwide deformation of all depositional strata. In onshore parts of Eel River Basin the Pleistocene and Holocene clays, sands, silts and gravels unconformably overlie the Wildcat Group sedimentary sequence.

Lithostratigraphy of the Point Arena Basin

The generalized lithostratigraphic column from the Point Arena Basin is shown on Figure 12. Pre-Cretaceous metasedimentary rocks constitute the basement of most of the basin. Only the southernmost part of Point Arena is thought to be underlain by granitic rocks of the Salinian block (Hoskins and Griffith, 1971). Thick Cretaceous sequences of shallow marine shale, siltstone and fine-grained sandstones crop out onshore in the southern part of the basin. These sediments thin to the north due to the pre-Eocene erosion. Eocene sediments display similar thinning trends to the north. The latter sequences are truncated by an erosional unconformity of lower Miocene age. The thick section of lower to upper Eocene age sandstone and shale found in the southern onshore part of the basin seems to suggest that a comparable section existed on the shelf but was removed during the erosional processes by the late Paleogene and early Neogene. Lower Miocene deep water marine shales, with thick but discontinuous basal sandstones resting on the unconformity, mark a sea transgression with deep marine deposition. These sediments are overlain by cherty shale deposits of middle Miocene age, similar to those in all Neogene basins along the California coast. Basal marine sandstones of a lower-upper Miocene age were deposited unconformably on older sediments near Point Arena cape. It appears however that the continuous sedimentation lasted between middle and upper Miocene in most of the Point Arena Basin. Upper Miocene marine siltstones and claystones grade upward into Pliocene marine sandstones. The Pliocene sandstones are separated from the coarser Pleistocene section by another unconformity. In central parts of the Point Arena Basin the thickness of sedimentary sequences of Tertiary age exceeds 3,300 m.

Ocean-floor Surface Sediments

Until the present time only a handful of investigations on the ocean-floor surface sediments have been conducted along the northern California continental margin. Field et al. (1980) presented the analytical results from samples of surface sediment collected at 63 stations in 1977 in offshore of northern California. The sediment grain size distributions in the Eel River Basin are shown in Figure 13. The diagrams presented show a general predominance of silt-size particles in the ocean-floor surface sediments. Silt usually constitutes 50 - 75% of the sediments while clay usually accounts for less than 25% and always for less than 40%. Sand-size particles usually account for less than 10% of the sediments. Locally, however, their content may exceed 75%. The sand distribution seems to be clustered, which is most likely related to bathymetric features or to the outcrops. Mud is the prevailing type of sediment across the entire margin. The exception is a belt which parallels the coast approximately 10 km wide where fine sands prevail, and muddy sand forming a narrow belt in the center of the shelf.

Surface sediments offshore of northern California have a mostly terrigenous provenance. Their principal sources are granitic and metamorphic rocks from the adjacent Klamath Mountains and Franciscan rocks of the northern California Coast Ranges. All these areas are drained by the coastal rivers which carry a substantial load of sediments to the Pacific Ocean.

The smear slides prepared from the ocean-floor sediment samples were found to contain diatoms. Their abundance varied from 5 to 75%. Foraminifera, calcareous nannofossils, radiolarians, and fish remains were also found in trace (1%) to common (5 - 25%) amounts (Field et al., 1980). Low content of calcium carbonate ($CaCO_3$) in the northern California shelf and plateau sediments reflects an unusually high influx of terrigenous material. Most samples show less than 2 wt.% of $CaCO_3$. Most of the $CaCO_3$ is derived from tests of foraminifera and calcareous nannofossils. With increasing distance from the shores, increase of the calcium carbonate in the ocean-floor surface sediments can be observed in northern California offshore. This is probably due to a progressive decrease in the amount of terrigenous material reaching those areas.

Rate of Sedimentation

The continental margin off northern California is a region with an active depositional regime. One of the apparent indicators of high sedimentation rate is widespread occurrence of relatively large size slumps. Also buried slumps identified in the region (McCulloch et al., 1982) are vivid proofs of high sedimentation rate in the geological past. The major rivers supply a significant amount of sediments to the offshore areas. Griggs and Hein (1980) estimated that the Smith, Klamath-Trinity, Mad and Eel Rivers, and Redwood Creek transport over 46 metric tons of sediment per year to the offshore. According to Brown and Ritter (1971) the Eel River drainage area alone has the highest sediment yield per square kilometer in the United States. The suspended sediment yield of the river is approximately 3,202 tons/km^2/yr. Large sediment plumes extending for more than 100 km into the ocean were revealed by LANDSAT studies in offshore areas of northern California (McCulloch et al., 1982). The calculations of the sedimentation rates based on thickness of Holocene sediments in the shelf area showed a rate of 0.5 to 1.0 cm/yr (Silver, 1969). Considering the fact that significant "losses" of the sediment occur through slumping, current winnowing, and other

AGE			MAX. THICK.	GRAPHIC LOG	DESCRIPTION
QUAT.	RECENT PLEIST.		1800'		Marine sands and gravels, minor clay, terrace deposits.
					UNCONFORMITY
TERTIARY	PLIOCENE	UPPER	2200'		Marine sandstones, thin-bedded, fine grained, rarely of reservoir quality. Oil sands onshore Pt. Arena.
TERTIARY	PLIOCENE ? MIOCENE	LOW. / UPPER	5000'		Marine siltstones and claystones. *Grain size generally finer with depth and distance from shore.* Occ. oil shows. Basal marine sandstone, erratic, thin.
					BASIN EDGE UNCONFORMITY
TERTIARY	MIOCENE	MID.	1100'		Marine shale, cherty. Common oil shows. Marine *sandstone, thin-bedded, fine grained, tight.*
TERTIARY	MIOCENE	LOWER	1800'		Marine shales, some oil shows. Marine sandstones, some of good reservoir quality, to 100' thick. Basal marine sandstone, erratic, tight, to 200' thick.
					UNCONFORMITY
TERTIARY	EOCENE		?		Erosional remnants of thick, deep to shallow marine sediments, which show evidence of deeper burial in pre-Miocene. *UE through LE section onshore west to San Andreas fault south of Pt. Arena.* 20,000' to 30,000' thick. Primarily sandstones with minor siltstones and conglomerates, some claystones. Volcanics, marine, basic.
					UNCONFORMITY
CRET.			?		Erosional remnants of thick, deep to shallow marine sediments, primarily silty shales and fine sandstones, dense.
					UNCONFORMITY
JUR.			?		*Metasediments ?*

Figure 12. **GENERALIZED LITHO-STRATIGRAPHIC PROFILE OF THE POINT ARENA BASIN**

After Hoskins and Griffiths, 1971

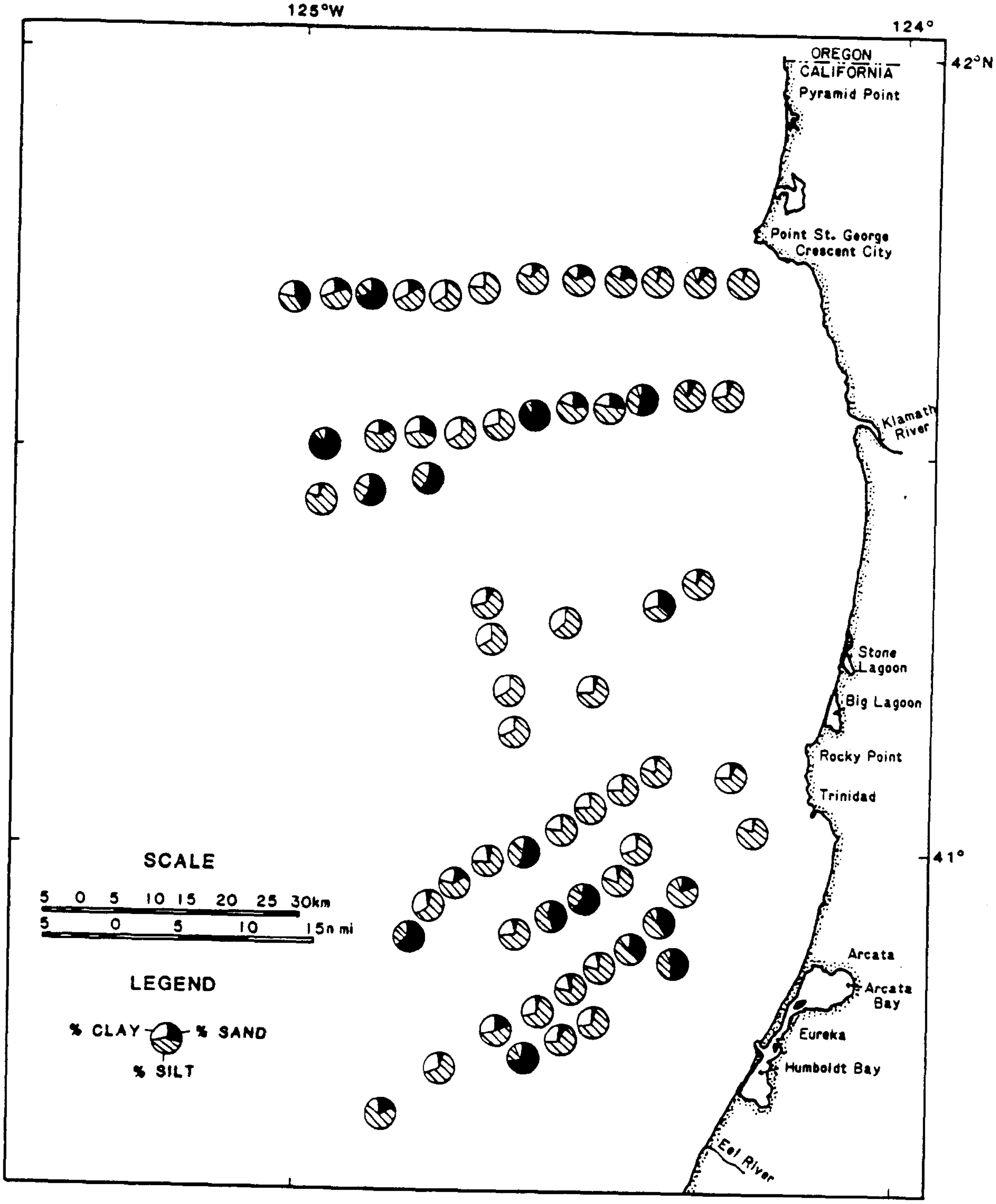


Figure 13. RATIOS OF SAND, SILT AND CLAY IN SEAFLOOR SURFACE SEDIMENTS, NORTHERN CALIFORNIA CONTINENTAL MARGIN

Modified after Field et al., 1980

process of down slope transportation, the effective rate of sedimentation must be higher than 1 cm/yr. Although the estimated rate of sedimentation in northern California offshore is high, nondeposition areas are also quite common. They are represented by elevated areas where erosion and transport of the sediments prevails over deposition. Also steep canyon walls must be included in the nondepositional areas.

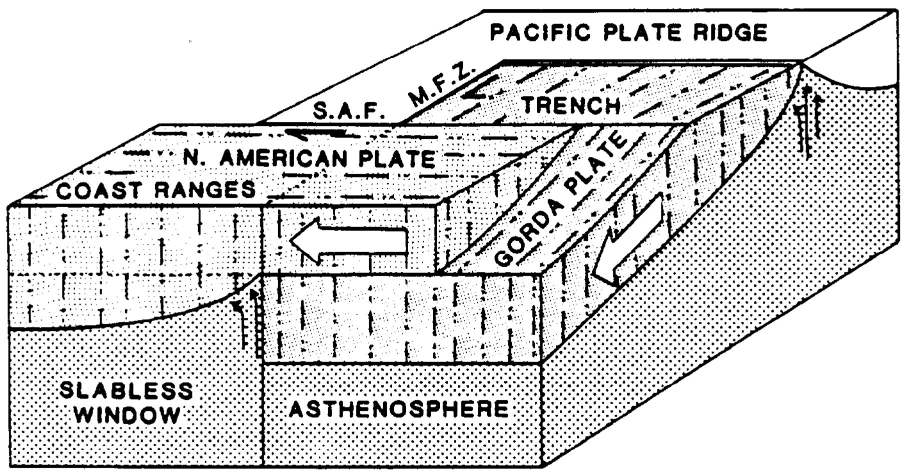
Heat Flow

The heat flow distribution in the western continental margins of North America probably has a quite diversified pattern (Lachenbruch and Sass, 1980). In recent years various authors have considered the thermal processes in California in conjunction with the plate tectonic history (e.g. Zandt and Furlong, 1982; Heasler and Surdam, 1985). Although all thermal models which have been developed are still too general for their application in detailed analysis of specific basins, they seem to provide the explanation for the regional trends of the heat flow distribution in the U.S. Pacific coastal provinces. The most noticeable feature of the heat flow pattern in California's coast is distinctively higher values (1.5 - 2.5 HFU) within and east of the San Andreas fault system. On the other hand in the coastal areas north of the Mendocino fracture zone, much lower values of heat flow (0.75 - 1.5 HFU) were measured (Figures 15 and 16). As has been described previously (p. 8), the tectonic development of the continental margin of northern California is strongly related to subduction of the Farallon plate which was followed by migration of the Mendocino triple junction (MTJ). At the present time active subduction is thought to occur north of the MTJ while right lateral slip movement is attributed to the Pacific coastal area south of the MTJ. Subduction of the Farallon plate in the past and presently the Juan de Fuca plate with its Gorda plate unit has caused a reduction of the heat transmitted to the surface within the arc-trench gap. Cold oceanic lithosphere (i.e. subducted plates) moving beneath the North American plate forms a thermal depression. The parameters which determine the magnitude of the temperature suppression are: rate of subduction, the angle of subduction and the thickness of the subducted lithosphere. According to Heasler and Surdam (1985) the passage of the MTJ affects the thermal regime in at least three ways:

a. removes the cooling effect of subducted oceanic lithosphere

b. the formation of the slabless window (Dickinson and Snyder, 1979; Figure 14) creates the void into which hot asthenospheric material (1,200°C) moves. The slabless window formed as a result of subduction and transform lateral motion of the adjacent Pacific and Gorda plates (Figure 14).

c. the movement between the Pacific and the North American plates and the dip of the subducted slab define geometry of the slabless window.



S.A.F. - SAN ANDREAS FAULT

M.F.Z. - MENDOCINO FRACTURE ZONE

ARROWS INDICATE MOTION RELATIVE TO FIXED PACIFIC PLATE

Figure 14. **IDEALIZED RELATIONS AMONG TECTONIC PLATES NEAR THE MENDOCINO TRIPLE JUNCTION**

Modified after Lachenbruch and Sass, 1980

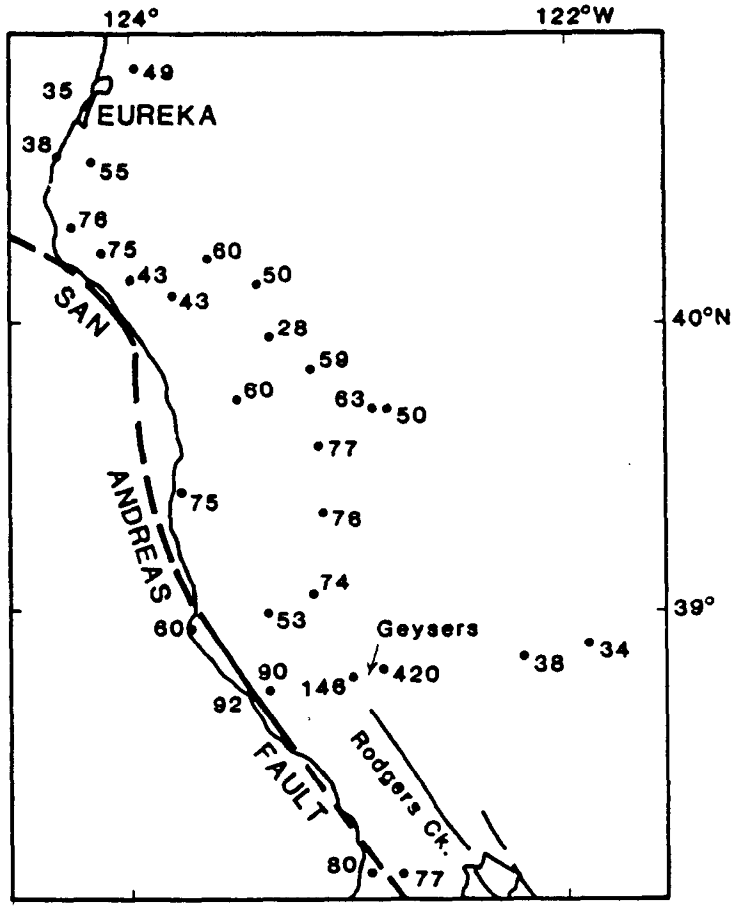


Figure 15. **MAP OF THE HEAT FLOW IN NORTHWESTERN CALIFORNIA, IN mWm^{-2} (1 H.F.U. - 41.8 mWm^{-2})**

After Lachenbruch and Sass, 1980

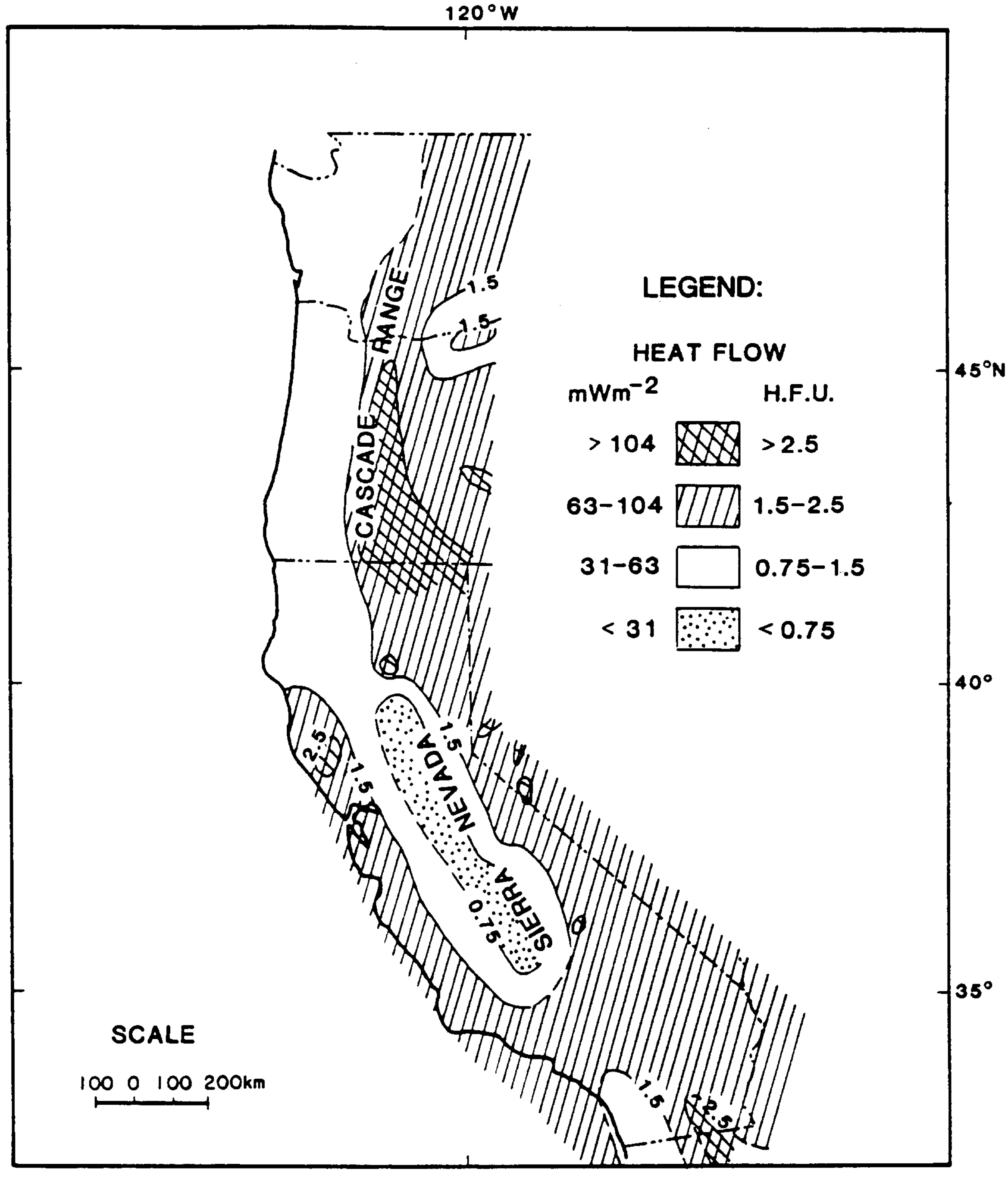


Figure 16. **A CONTOUR MAP OF HEAT FLOW IN WESTERN UNITED STATES**

Modified after Lachenbruch and Sass , 1980

Hydrocarbon Occurrence

Exploration activities for oil and gas in five Tertiary basins offshore of central and northern California took place prior to the OCS Lease Sale 53. Following May 14, 1963, Lease Sale 53, nineteen exploratory wells (including 4 wells in Eel River Basin and 3 wells in Point Arena Basin) were drilled in all five basins. All of them were abandoned as no significant hydrocarbon accumulations were encountered (McCulloch et al., 1977). The offshore California basins extend into the onshore areas. The oil and gas production from the onshore basins has been relatively small. Some authors (Graham, 1976; Hall, 1975) claimed that the onshore basins are separated from their offshore equivalents by major faults with considerable strike-slip displacements along them.

Eel River Basin and Humboldt Basin

Humboldt Basin is the onshore extension of Eel River Basin to the southeast and constitutes 10% of the entire basin. Only an insignificant amount of oil and gas has been produced from the Humboldt Basin. According to the reports of the California Division of Oil and Gas (1976) through December 1975, Tompkins Hill field produced 63 billion cubic feet of gas and Table Bluff field produced only 0.1 billion cubic feet of gas. In both fields the gas producing strata were the Pliocene Del Rio Formation which consists of very fine-grained sands. Only 350 barrels of oil had been produced from the stratigraphic trap in Upper Cretaceous. Lithologically the producing strata are sandstone and shale (McMulloch et al., 1982).

The Miocene cherty shale considered as the source for hydrocarbon generation in basins to the south has not been found in the offshore area of Eel River Basin. Hoskins and Griffith (1971) indicated the possible widespread hydrocarbon source rock in Eel River Basin mainly for two reasons:

a. lithologically the Eocene strata are represented by well indurated, fine-grained marine sediments with graywacke and conglomerate

b. spatial distribution of the Eocene strata seems to be represented by irregular scattered erosional remnants left on the Franciscan basement.

In this situation the most probable strata which could generate hydrocarbons belong to the upper Miocene/lower Pliocene Wildcat Group (Figure 11) composed mainly of marine mudstones and siltstone. The recognition of hydrocarbon presence in the Eel River Basin is based on seismic evidence and on analysis of gases from near bottom sediments. Field et al. (1980) interpreted decreased acoustic velocities in near sea floor surface sediments in several seismic sections as the area with shallow gas. According to those authors one such area is located on the shelf west of Crescent City. High resolution seismic sections from this area display masking features of subbottom reflectors. Similar features indicating possible accumulations of shallow gas have been found in the areas off Eureka. Field et al. (1980) reported on gassy sediment cores from near-bottom marine sediments in the vicinity of a diapir on the outer plateau. The analysis of this gas has shown "relatively high concentrations of methane gas (probably biogenic in origin)". Kvenvolden and Field (1981) presented the results of the hydrocarbon analyses of gas recovered in two locations from unconsolidated sediments ponded in the depressions on the surface of a shale diapir in the southern offshore Eel River Basin. Four lines of evidence indicate that the recovered gas was of thermogenic origin:

1. High concentration of ethane through butane homologues
2. Isotopic composition of methane carbon $\delta^{13}C_1$ equal -44 to -43 ppt, relative to PDB standard
3. Presence of gasoline-range hydrocarbons (C_{5+})
4. Presence of heavy hydrocarbons containing n-alkanes

It is believed that the above mentioned hydrocarbons originated deep within the basin and their migration to the surface is mainly controlled by fractures and faults generated during diapir emplacement.

Point Arena Basin

Oil shows are common in shales and cherty shales of the middle and upper Miocene strata (McMulloch et al., 1982). Deep water marine sands of lower Miocene and Pliocene age appear to be the most prospective hydrocarbon reservoirs in the Point Arena Basin. Despite the favorable structural conditions (e.g. folds bounded by high-angle reverse faults) three wells located on seemingly prospective structures in southwest part of the basin were found to be dry.

Detailed evaluation of the hydrocarbons in both above presented basins is not possible at the present time. More data are needed for precise evaluation of structural, lithological and geochemical controls in hydrocarbon generation, migration and accumulation.

Organic Matter

The presence of organic matter is one of the indispensable conditions for hydrocarbon gas generation. Broad discussions pertaining to biogenic methanogenesis and its relation to gas hydrate formation were presented in a series of our previous reports (Krason and Ridley, 1985; Krason and Ciesnik, 1986). Most of the authors have indicated that a minimum of 0.5% organic carbon is needed to sustain biogenic methanogenesis. The analyses of the organic carbon in sea-floor sediment samples in Eel River Basin showed the values ranging from 0.5% to about 1.5% (Field et al., 1980). Most samples contained 1.0% ± 0.2% by weight of the organic carbon and only two samples showed this value exceeding 2%.

The existing data on the organic matter distribution in the continental margin of northern California are still very fragmentary and incomplete. Review of these data suggests their conformity with the opinion that the sediments are mostly terrigenous and general potential for hydrocarbon generation is poor.

Discussion

The continental margin of northern California represents a young and tectonically active region. The reconstruction and understanding of the sequence of geological events in a region's evolution constitutes an important factor in successful evaluation of the gas hydrate potential of an area.

Although the probability of gas hydrate occurrence in the northern California offshore south of the Mendocino fracture zone is slim, Point Arena Basin has been deliberately incorporated into the study area. The intention of such approach was an attempt to pinpoint various geological factors which might lead to gas hydrate formation north of the Mendocino fracture zone and those which probably prevented their generation in the area south of the Mendocino fracture zone.

During geological evolution of the continental margin of northern California, some elements played a particularly important role in the process of gas hydrate formation and stabilization:

- tectonic position of the region
- sedimentary environments
- structural deformation
- shale diapirism
- hydrocarbon generation and migration

All the above listed geological elements greatly determine the presence of favorable or unfavorable conditions for gas hydrate formation. Among those conditions the most important are:

- thermal regime in the hydrate formation zone
- pressure conditions
- hydrocarbon gas supply to the hydrate formation zone

With regard to tectonic position the continental margin of northern California represents two distinctly different subregions. The Mendocino fracture zone as the northwestern extension of the San Andreas fault separates the continental margin with active subduction of the Gorda plate from the margin where right-slip lateral movement of the Pacific plate prevails. This difference has a direct bearing on the type of geothermal regimes in the two types of continental margins. As it has been shown in the thermal model developed by Lachenbruch and Sass (1980), heat flow is lower in continental margins where subduction processes take place. This fact is explained by the cooling effect of the subducted oceanic plate. Conversely, the continental margin south of the Mendocino fracture zone features higher values of the heat flow which Lachenbruch and Sass (1980) explained by the presence of the slabless window on the boundary between asthenosphere and the continental crust (Figure 14). This window allows hot asthenosphere to move closer to the upper crust surface.

The significance of various thermal regimes lies not only in the range of temperatures under which gas hydrates may form but also in the field of thermogenic hydrocarbon generation. It seems that the hydrocarbon generation window may exist in lower sedimentary sequences of Eel River and Point Arena basins. The distribution and quality of the potential source rocks are poorly known and more data are needed for their proper assessment. The existing data from both subregions have not revealed source rocks with good potential.

Review of the lithostratigraphic profiles in Eel River and Point Arena basins, which occupy the greater part of the northern California offshore, gives the prospect of altering sedimentary environments in the region. The most characteristic feature of the lithological profiles is relatively wide presence of terrigenous sediment deposited mostly in fairly shallow marine environments. Type of sediment may have at least a dual role with regard to gas hydrate formation:

a. change of pore water vapor pressure (Makogon, 1974). The experimental studies on gas hydrate formation in porous environment performed at the Gubkin Petrochemical and Gas Industry Institute in Moscow showed that with smaller diameter rock grains (i.e. smaller capillary radius) lower temperature is required to form the hydrate. This fact is due to the increase of depression of water vapor pressure with decreasing grain size of the host rock.

b. modifying heat flow. The relationship between the type of sediment and its thermal conductivity has been discussed by MacLeod (1982). It has been proven that with an increasing sand/shale ratio, thermal conductivity increases.

Impact of the first factor is probably uniform throughout the northern California offshore. The second factor may locally cause depression of the geoisotherms, lowering the base of the gas hydrate zone, particularly in Eel River Basin where large areas with shale diapirism were revealed.

The structural features of studied areas may constitute an important factor with regard to gas hydrate formation. Except the apparent significance of folding and faulting systems which can form structural traps in the hydrate zone (e.g. Messoiakh gas hydrate field), faults often constitute hydrocarbon migration channels supplying the gas to the hydrate formation zone. The analysis of hydrocarbon gases extracted from the ocean-floor sediments in Eel River Basin, jointly with widely present faults, certainly creates such a possibility.

A general review of the important geological factors with regard to gas hydrate formation in the northern California continental margin north and south of the Mendocino fracture zone seems to indicate that thermal regimes are noticeably different in both areas. Therefore geothermal gradients should probably be considered as a major factor controlling gas hydrate potential in northern California offshore.

PART II

FORMATION AND STABILITY OF GAS HYDRATES

Northern offshore of California had been listed by Kvenvolden and Barnard (1983) as one of 24 locations with presumed gas hydrate occurrence. The evidence for the gas hydrate presence in this region is based entirely on seismic data which revealed widespread bottom simulating reflectors (BSRs) underlying the inner continental margin of northern California (Field and Kvenvolden, 1985). Although there is satisfactory seismic data with regard to BSRs in the region, many direct factors controlling gas hydrate formation and their stabilization are still inadequately known for the lack of indispensable data. Known geological factors which in our opinion might have affected the presence of gas hydrates in the continental margin of northern California were recapitulated in previous chapter. Therefore the following chapters will be focused on seismic evidence and thermodynamic conditions of gas hydrate formation in the region.

Seismic Evidence

Seismic data have been the foremost source of information in the process of gas hydrate identification. The anomalous seismic reflections often referred to as bottom simulating reflectors (BSRs) have been described by numerous authors as the base of gas hydrates (Stoll et al., 1971; Ewing and Hollister, 1972; Shipley et al., 1979; Dillon et al., 1980; Kvenvolden and McMenamin, 1980; and others). The configuration of the gas hydrate base which separates the zone with solid gas hydrates and that containing free gas is determined by geothermal regime. As the phenomenon is thermally controlled, BSRs are relatively easy to distinguish where they cut across stratification lines. Conversely in the areas where BSRs may parallel stratification their recognition is difficult. Probably the most difficult dilemma in distinguishing BSRs related to gas hydrates is the fact that similar anomalous seismic reflections may be obtained from diagenetic boundaries (Hein et al., 1979). It is widely accepted that diagenetic processes that are also thermally controlled such as transformation of the biogenic opal A into crystalline opal CT can produce such "deceitful" boundaries. Shipley et al. (1979) proposed three seismic features characteristic for the BSRs produced by the base of gas hydrate zones:

a. reflection polarity reversal
b. large reflection coefficient
c. increased subbottom depth of the BSR with increasing water depth

The reader will find a more detailed discussion on the nature of gas hydrate-related BSRs in our reports of this series from the Bahama Outer Ridge and the Panama Basin (Krason and Ridley, 1985; Krason and Ciesnik, 1986).

In 1985, Field and Kvenvolden published the map of BSR occurrence in the northern California continental margin (Figure 17). This map is based on a complete set of seismic data generated by the U.S. Geological Survey during the surveys in northern California offshore in 1977, 1979 and 1980. According to this study, most single-channel and air-gun seismic reflection records from the area show BSRs. The BSRs had been mainly observed beneath the Klamath Plateau and upper continental slope. The eastern boundary for BSR occurrence is the isobath of 800 m. The maximum water depth at which BSRs were identified is 2,000 meters at western limits of the BSR area. In some sections the western boundary of this area is uncertain due to steep slope. In a northern direction, the area of well defined BSRs extends to the continental margin of Oregon while its southern tip reaches the latitude of Eureka (Figure 17). The entire zone with identified BSRs covers at least 3,000 km^2.

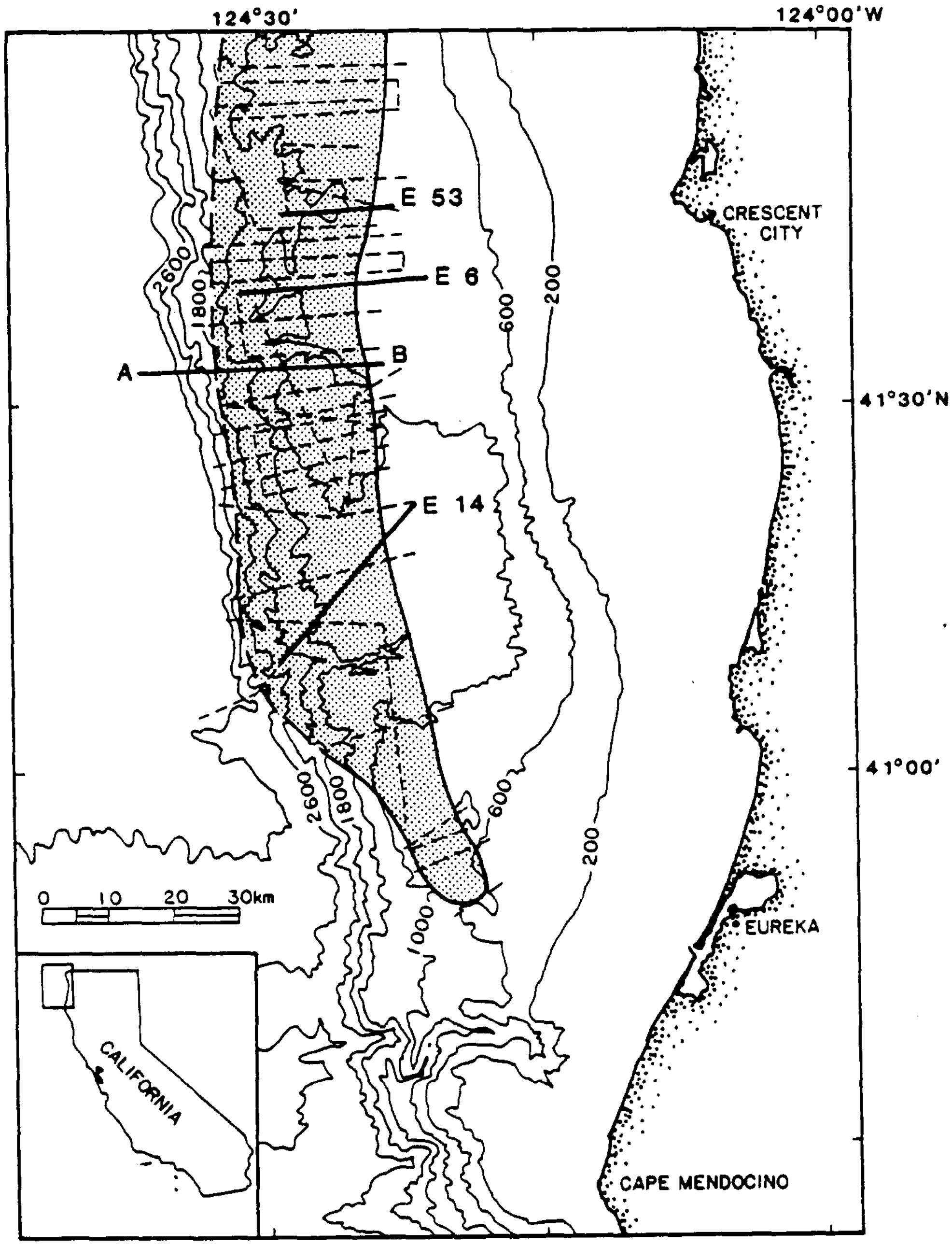
In the area south of the Mendocino fracture zone, significantly less seismic data are available within Point Arena Basin. Review of this data has not disclosed BSRs. Although it is premature to discard the possibility of BSR occurrence in Point Arena Basin and in the adjacent continental slope, the likelihood of their presence is low.

Some seismic lines from Eel River Basin and the adjacent areas are shown on Figures 19, 20, and 21. All sections display well defined anomalous reflectors which show distinctive features of being related to the base of gas hydrates. The position of randomly chosen BSRs relative to the gas hydrate stability curve is also shown on Figure 23.

Line E-14 (Figure 18). This seismic profile represents the area of southwestern Klamath Plateau and adjacent westward continental slope. The ocean water column varies from 1,100 to 1,830 m. BSRs are easy to delineate along the entire profile length with the exception of its extreme northeastern section. Increasing with the ocean depth, acoustic depths of BSRs range from 0.31 to 0.34 sec. Again assuming the acoustic velocity in these sediments as 1,700 m/sec, the thickness of the hydrate zone turns out to be 232 - 255 m.

Line E-6 (Figure 18). The bottom simulating reflector is noticeable along approximately 75% of the profile. The water column above the sea floor varies from 640 to 1,120 m. The acoustic depth of the BSR ranges from 0.25 to 0.29 sec (two-way travel time). Assuming acoustic velocity in unconsolidated sediment of 1,700 m/sec, the hydrate zone in the presented line is 212 to 246 m thick.

Line A-B (Figures 19 and 20). This line encompasses the entire outer continental margin including the abyssal plain, continental slope, western edge of the Klamath Plateau with western part of the Eel River Basin. Subsequently the line comprises the area where depth of water column varies in wide spectrum from 910 to 2,900 m. Well defined BSRs can be traced from Eel River Basin westward to the lower continental slope, i.e. to approximately 2,800 m below sea level. Within Eel River Basin, tracing BSRs becomes difficult as the sediments are horizontally stratified. The acoustic



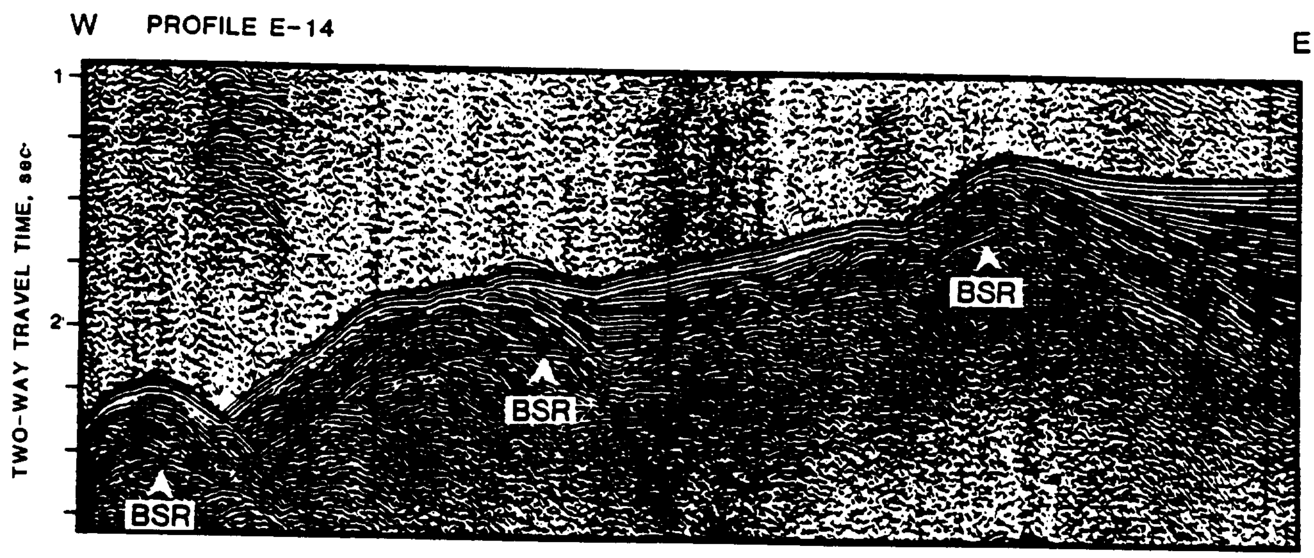
DASHED SEAWARD BOUNDARY OF THE BSRs AREA SIGNIFY ITS POOR CONTROL ON SEISMIC SECTIONS

PROFILES ALONG THE LINES E 53, E 6, A-B, AND E 14 ARE SHOWN IN FIGURES 18-21

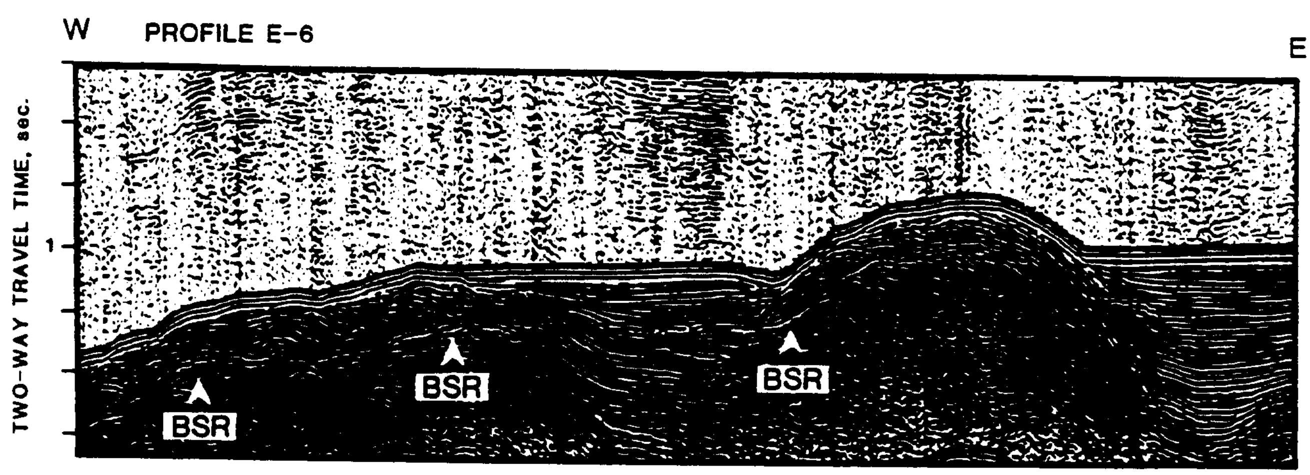
BATHYMETRIC CONTOUR INTERVAL IS 400 m

Figure 17. MAP OF THE BSR (BASE OF INFERRED GAS HYDRATES) OCCURRENCE IN THE CONTINENTAL MARGIN OF NORTHERN CALIFORNIA (SHADED AREA) AND SHIPTRACK COVERAGE

Modified after Kvenvolden, 1985



FOR PROFILE LOCATION SEE FIG. 17



FOR PROFILE LOCATION SEE FIG. 17

Figure 18. SPARKER (160 kJ) SEISMIC REFLECTION RECORDS ILLUSTRATING PRESENCE OF BSRs OFFSHORE NORTHERN CALIFORNIA

After Field and Kvenvolden, 1985

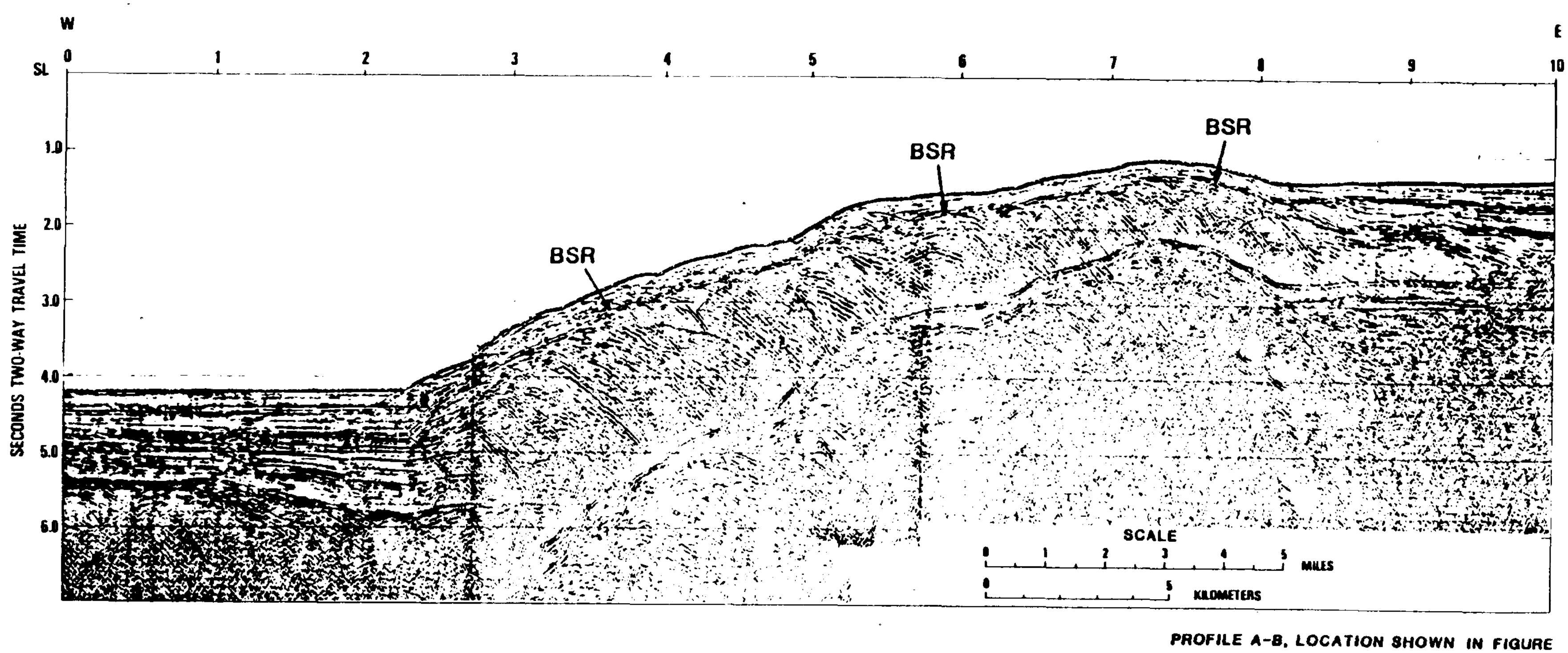


Figure 19. **STRUCTURE OF SUBDUCTION COMPLEX, OFFSHORE NORTHERN CALIFORNIA**

After Biddle and Seely, 1983

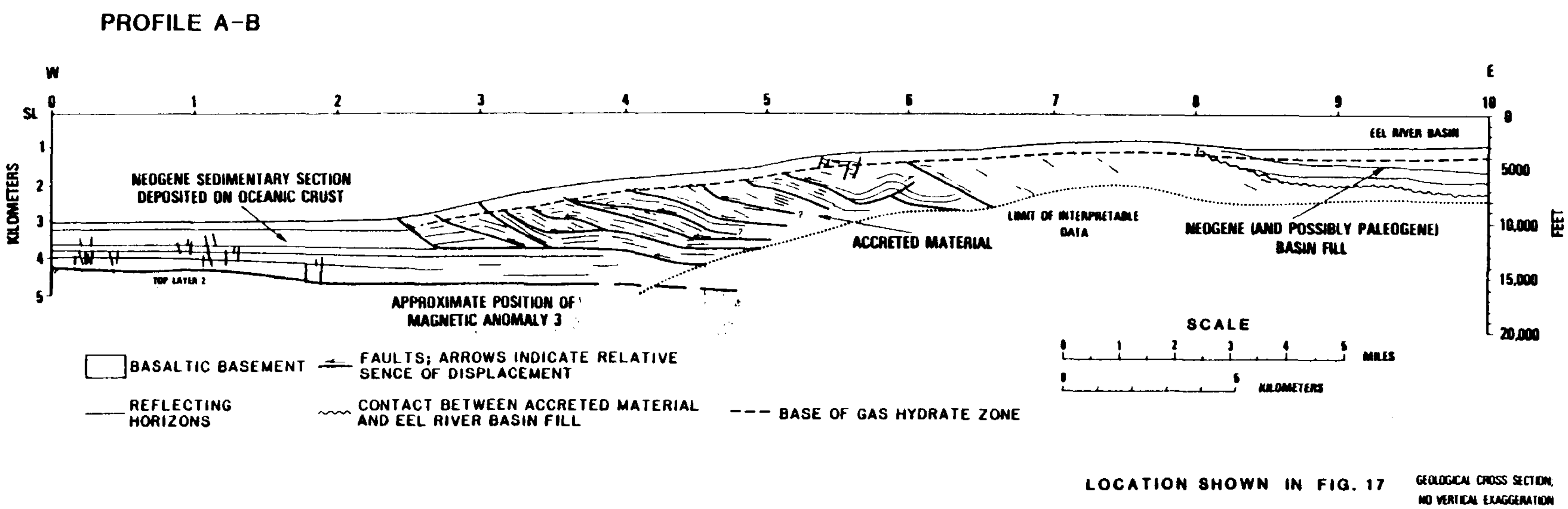


Figure 20. STRUCTURAL INTERPRETATION OF SEISMIC PROFILE A-B, OFFSHORE NORTHERN CALIFORNIA

After Biddle and Seely, 1983

depth of the BSRs ranges from 0.22 to 0.34 sec showing the trend of increased values with increasing depth of the ocean.

Line 53 (Figure 21). Bottom simulating anomalous reflectors can be traced only in the western section of the profile where ocean water column is 830 - 850 m. The acoustic depth of the BSRs is within 0.25 - 0.27 sec.

Equilibrium Conditions of Gas Hydrate Formation

The equilibrium of gas hydrate formation at the free water-gas interface is mainly dependent on temperature (T) and pressure (P). Porous environment and multicomponent gas change, at times significantly, the equilibrium values of T and P. The modifying role of both factors had been discussed in one of our reports entitled "Gas hydrates in the Russian literature." In general it has been found that in a porous environment lower temperatures and higher pressures are required for gas hydrate stabilization compared with a free gas-water interface environment. Gas hydrates formed from the multicomponent gases need noticeably lower pressures and higher temperatures for stabilization (Makogon, 1974).

Many experimental attempts have been made in order to establish P-T equilibrium values for various gas hydrates (i.e. Lutoshikin and Bukhalter, 1969; Makogon, 1974; and others). These attempts resulted in variety of the equilibrium diagrams and equivalent equation. One such diagram is shown on Figures 22 and 23. The curves were constructed for the continental margin of northern California on the basis of the experimental data obtained by Holder (1983) for thermogenic gas. In spite of the fact that Holder's data were produced experimentally on a free water-gas interface, the superimposed positions of the presumed base of gas hydrates derived from seismic profiles (Figures 6, 17, 18) fit quite well the curve appropriate for the area with a geothermal gradient of 5.5°C/100 m.

Assessment of Gas Resources in Gas Hydrates

The recognition of gas hydrates in the northern California continental margin is based entirely on the identification of seismic bottom simulating reflectors (BSRs). Existing geological data seem to confirm the possibility of the gas hydrates in the California offshore north of the Mendocino fracture zone. Detailed establishment of a role of all geological factors controlling gas hydrate formation and stability requires more survey and studies which must include drilling.

It has been estimated that the area with identified BSRs (i.e. presumably gas hydrates) extends for at least 3,000 km^2 throughout the continental margin of California north of the latitude 40°45'N (Figure 17). Assuming 40% sediment porosity and 12% pore space filling, 5% of the sediment volume will be saturated with gas hydrates. Furthermore applying the gas volume conversion factor from gas hydrates 200:1 estimated by Kuuskraa et al. (1983) for standard conditions the gas resources in the hydrate state should amount to:

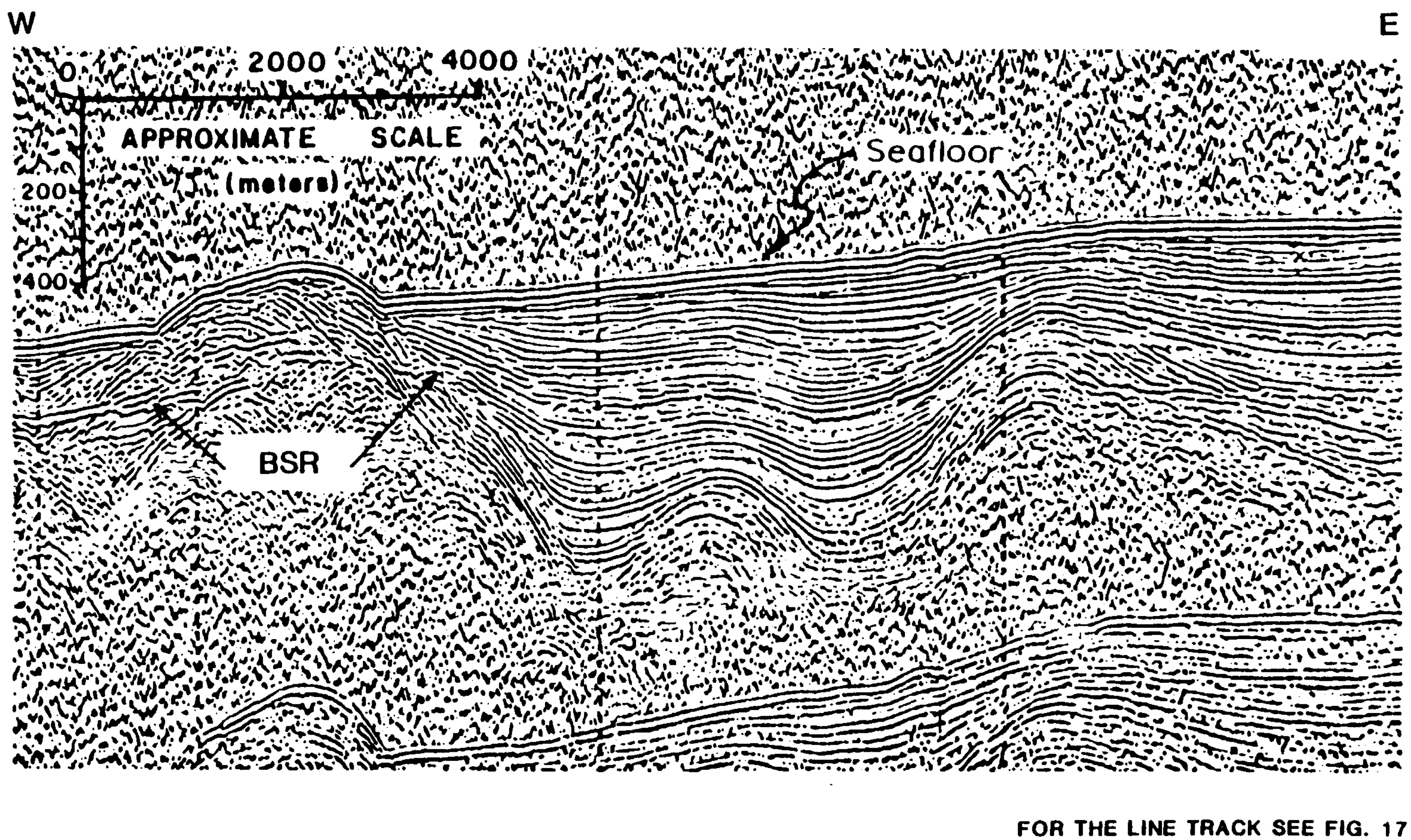


Figure 21. SPARKER RECORD FROM THE OUTER KLAMATH PLATEAU, OFFSHORE NORTHERN CALIFORNIA

After Field et al., 1980

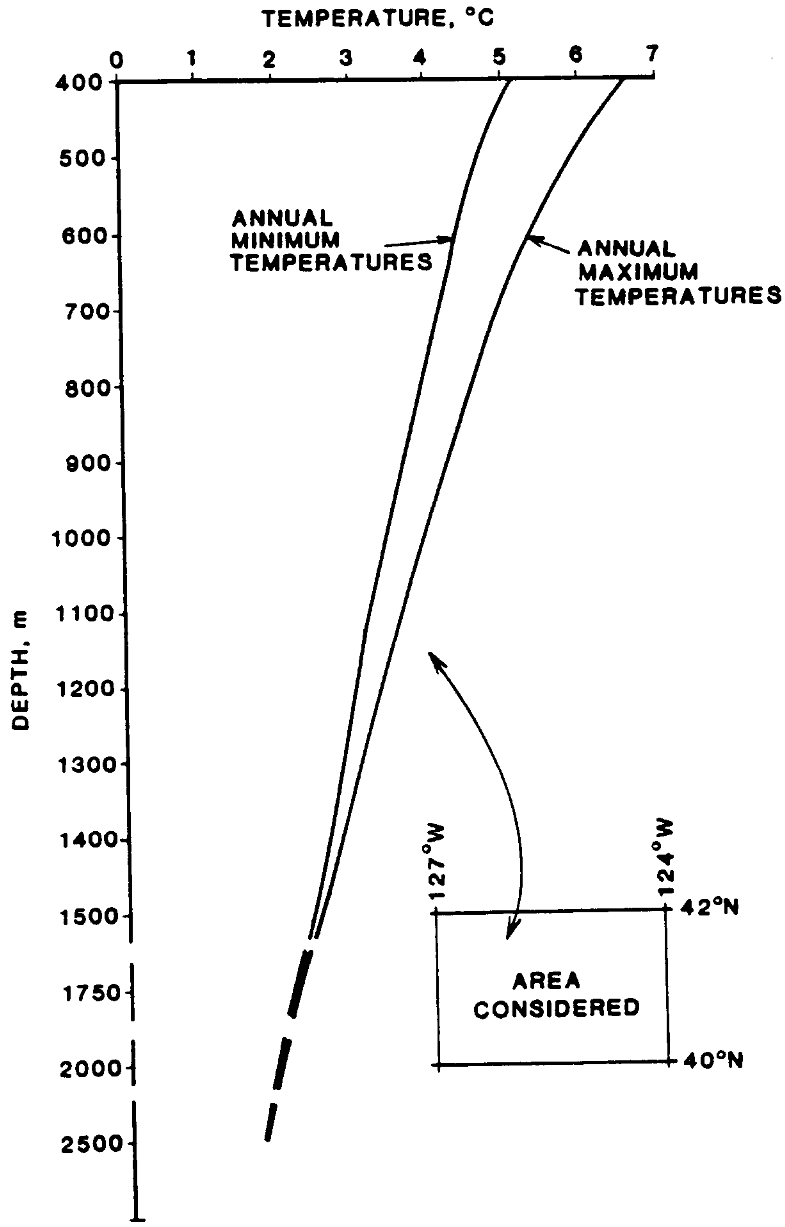
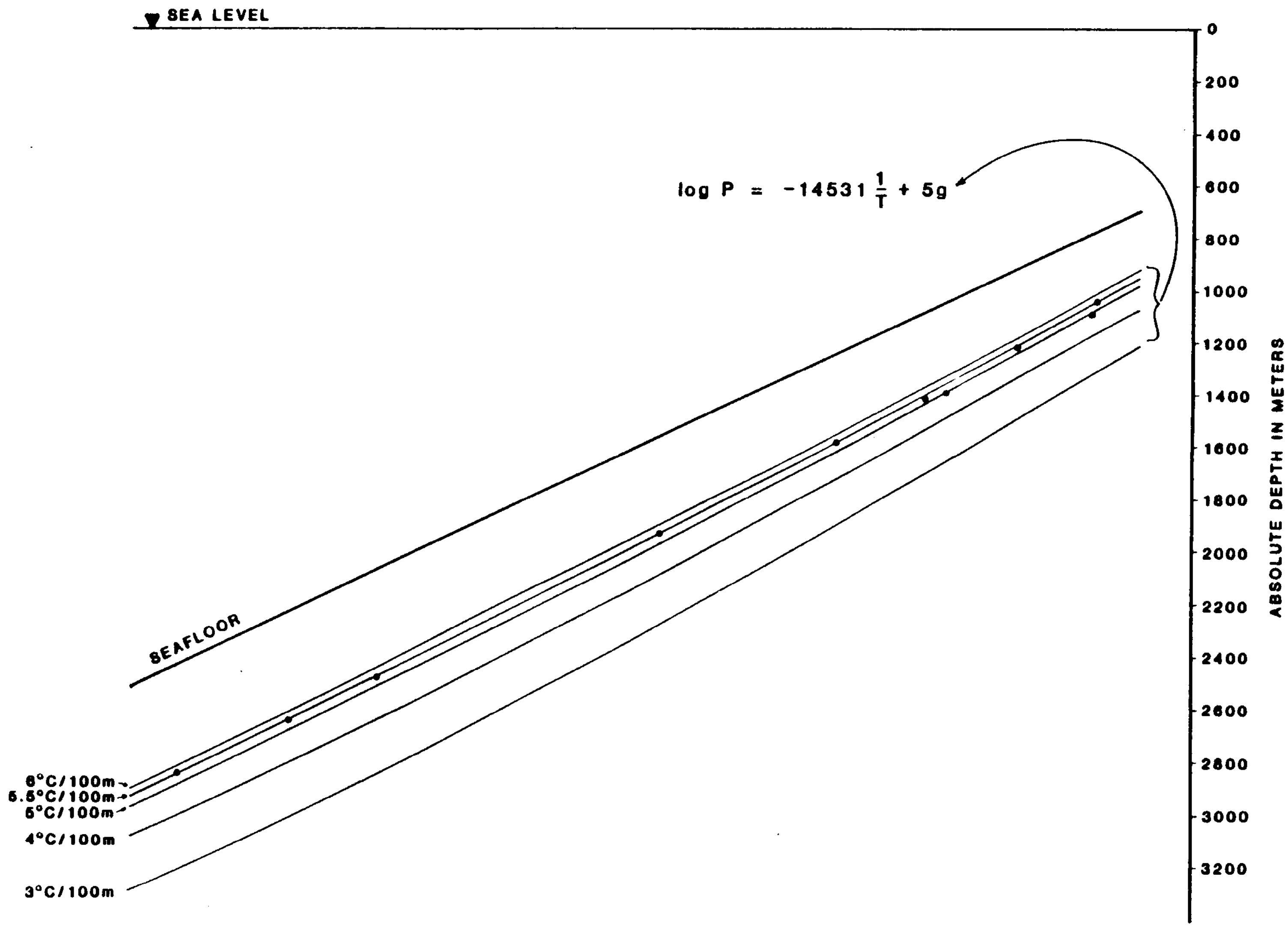


Figure 22. TEMPERATURES IN OCEAN WATER COLUMN, OFFSHORE NORTHERN CALIFORNIA

After Churgin and Halminski, 1974



Curves are based on experimental data by Holder (in Handbook of Gas Hydrate Properties and Occurrence, 1983) and the equation formulated by Finley.

Thermocline of the sea water column used in the study region is shown in Figure 22

Dots indicate the position of BSRs from seismic sections shown in Figures 18-21

Figure 23. STABILITY CURVES FOR THERMOGENIC GAS HYDRATES IN NORTHERN CALIFORNIA CONTINENTAL MARGIN FOR VARIOUS ASSUMED GEOTHERMAL GRADIENTS

$$1 \text{ m of sediment thickness} \times 3 \times 10^{9} \text{ m}^{2} \text{ area} \times 5\% \text{ hydrate} \times 200 \text{ volume conversion factor} = 3 \times 10^{10} \text{ m}^{3} \text{ (1.06 TCF)}$$

Average thickness of gas hydrate zone in the considered area is approximately 200 m. Subsequently assuming that gas hydrates occupy 40% of the pore space of the region, the total estimated gas resources are:

$$200 \times 3 \times 10^{10} \times 0.4 = 2.4 \times 10^{12} \text{ m}^{3} \text{ (84.7 TCF)}$$

Conclusions

The above presented study results show how ubiquitous gas hydrates may be in the region of the continental margin of California. The review of the critical geological factors controlling gas hydrate formation and stability is based on limited existing data. Therefore the study must be considered as preliminary while more pertinent data will be gathered. The following conclusions related to gas hydrate formation and stability in northern California offshore can be drawn from the presented material:

1. Continental margin of northern California encompasses two distinctive tectonic subregions separated by the Mendocino fracture zone:

    a. northern subregion with active subduction,

    b. southern subregion where the right-slip lateral movement prevails.

2. Tectonic position of the two subregions jointly with two different types of underlying basement determined to a significant degree the type of strata deformation, i.e. number of faults is greater in southern Point Arena Basin underlain by granitic basement while folding prevails in a predominant part of the region underlain by metasedimentary rocks of Franciscan Group.

3. The accretionary edge of the continental margin adjacent to Eel River Basin has the imbricated structure containing thrust faults dipping in a landward direction.

4. The shale diapirism associated with faults appears on the western edge of Eel River Basin and to a lesser degree in the interior of the basin.

5. Mostly terrigenous material and a relatively low content of organic matter characterize lithologic profiles of Eel River and Point Arena basins.

6. The two basins represent areas with unusually high sedimentation rates.

7. Lachenbruch and Sass' model of thermal regimes in the subregions north and south of the Mendocino fracture zone (MFZ) does not quite fit the geothermal gradients calculated from the gas hydrate stability relationship. In the continental margin north of MFZ the above mentioned model predicts relatively low heat flow within range of 1.5 - 2 HFU (low geothermal gradient), while the gas hydrate stability calculations indicate the geothermal gradient 5.5°/100 m which corresponds to higher than 2 HFU heat flow.

8. Analyses of hydrocarbon gas extracted from near bottom sediment samples suggest its thermogenic origin.

9. Faulting systems seem to constitute a major controlling factor in hydrocarbon migration processes.

10. While bottom simulating reflectors (BSRs) are widespread in Eel River Basin, they are not evident in Point Arena Basin. Significantly higher geothermal gradients in Point Arena Basin as well as lack of apparent source of hydrocarbons are among the most probable explanations.

11. Average thickness of the gas hydrate zone in California offshore north of the Mendocino fracture zone is approximately 200 m, based on seismic and other pertaining data (Figure 23).

12. The estimated gas resources accumulated in the presumed gas hydrate zone equal 84.6 TCF.

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